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COMPREHENSIVE STUDY OF SPECIFIED AIR POLLUTION SOURCES TO ASSESS THE ECONOMIC IMPACT OF AIR QUALITY STANDARDS ASBESTOS, BERYLLIUM MERCURY

VOLUME II

RESEARCH TRIANGLE INSTITUTE

PREPARED FOR
ENVIRONMENTAL PROTECTION AGENCY

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Volume II

COMPREHENSIVE STUDY OF SPECIFIED AIR POLLUTION SOURCES TO ASSESS THE ECONOMIC IMPACT OF AIR QUALITY STANDARDS ASBESTOS, BERYLLIUM, MERCURY

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by

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Prepared for

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STUDY OF SPECIFIED HAZARDOUS POLLUTION SOURCES TO ASSESS THE ECONOMIC EFFECTS OF AIR QUALITY STANDARDS

by

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ABSTRACT

Estimates are made of the costs of controls to reduce the emissions of asbestos fibers, beryllium, and mercury from primary production and selected secondary sources within the Nation. Production processes and control technology are examined. Controls are selected to meet assumed or proposed emission standards and costs are estimated. In addition, an extended analysis is made where appropriate, to determine the economic impact of control costs on each industrial source or group of industrial sources studied. The effects on prices are also estimated. Under the assumed implementation plan, the estimated costs are those that will be incurred during the period of Fiscal Year 1970 through Fiscal Year 1977.

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CHAPTER I

OVERVIEW

I. Introduction

Under section 112 of the Clean Air Act, as amended, the Administrator of the Environmental Protection Agency has designated asbestos, beryllium and mercury as hazardous air pollutants. National emission standards have been proposed for certain source categories known to emit these pollutants. Section 312a of this act requires annual estimates of the cost of efforts for controlling air pollution.

This report provides estimates of the costs and economic impact of implementing air pollution control measures applied to selected asbestos, beryllium and mercury emission sources.

A. Health Importance

Hazardous air pollutants may cause or contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness. Asbestos, beryllium, and mercury are very different in the number and type of sources, their effects on health and the control options available.

The primary danger from asbestos is inhalation of the fibers into the lungs. A high incidence of lung cancer, pleural or peritoneal mesothelioma, and asbestosis are all strongly correlated with exposure to atmospheric asbestos. Asbestos is unique among the hazardous substances, however, in that it does not have an acute toxicity. Beryllium is highly toxic in all forms (except possibly beryl) causing a serious chronic lung disorder in susceptible persons. The poisoning action of mercury is cumulative or chronic similar to lead poisoning. Large doses of the metal or small doses of some of its more toxic compounds, however, can produce acute poisoning.

B. Economic Importance

Asbestos, beryllium, and mercury have properties that make them uniquely suitable for special applications in a modern industrial society.

The properties making asbestos so useful are its long, extremely fine and flexible fibers, which are thermally. electrically, and chemically inert, high in tensile strength and have favorable frictional properties. Asbestos is used in over three thousand products ranging from heat-resistant textiles to vehicle brake linings. It is used as a filler in plastics, for filters in many industrial applications, in insulation, and to strengthen many products as in asbestos-cement pipe and building board.

Beryllium metal has exceptional strength and rigidity with a high strength-to-weight ratio and important thermal and nuclear properties. Beryllium is widely used to harden copper and aluminum much as carbon is used to harden iron into steel.

Mercury is the only metal which is liquid at most temperatures. It has a uniform volumetric expansion coefficient as a liquid and it is an electrical conductor. Although it is relatively inert chemically, it will amalgamate with nearly all other metals (iron being a useful exception). Mercury is widely used, but the leading uses have been the electrolytic preparation of chlorine and caustic soda, in electrical apparatus, in paint for mildew proofing, and in industrial and control instruments.

II. Study Methods

A. Control Standards

This study was started before control standards were proposed for the hazardous pollutants. Control standards were therefore assumed based on the best information available.

For asbestos, the control assumed for this study was to pass all asbestos containing exhaust air from a plant or manufacturing facility through an adequately maintained fabric filter of appropriate design. The assumed control is somewhat more comprehensive than that subsequently proposed under which more latitude is allowed in the choice of filter, and some processes involving bound asbestos may be excluded from compliance with dust collection device requirements.

Under the assumed beryllium standard, total emissions shall not exceed 10 grams of beryllium in a 24 hour day, or outplant concentrations shall not exceed 0.01 micrograms of beryllium per cubic meter of air averaged over a 30 day period. The standard assumed for beryllium was

the same as that used by the Department of Defense and the Atomic Energy Commission for many years. This standard is the one later proposed for beryllium.

For mercury the emission standards assumed in this study are as follows:

Ore processing: Emissions are not to exceed 0.95 g/metric ton (0.0021 lb/ton) of ore processed and no more than 1156 g/day (2.56 lb/day) for any one plant.

Secondary processing: Emissions are not to exceed the new industrial hygiene TLV (Threshold Limit Value) of 2.85-5.5 mg/min. for any one plant.

Mercury cell chlor-alkali plants: Emissions are not to exceed 0.005 lb of mercury per ton of chlorine produced and no more than 2.56 lbs per day from any one plant.

The emission standard adopted for ore processing and facilities using mercury chlor-alkali cells is that emissions to the atmosphere from sources subject to controls not exceed 2,300 grams of mercury per 24 hour period (5.0 pounds per 24-hour period). No standard was adopted for secondary mercury processors. The standard adopted is significantly less stringent than the standards assumed for this report. Costs and economic impact significantly below those reported would appear, therefore, to be appropriate.

B. Cost Estimation and Economic Impact

In general, control costs were estimated by calculating the expenditure required to increase the levels of emission control from an assumed baseline level to the level required for compliance with the selected emission control regulations. This approach is based on the premise that the costs properly attributable to the implementation of the Clean Air Act, are those costs incurred in reaching control levels not commonly being achieved at the time these industries came under amendments to the Clean Air Act.

The number and type of installations currently controlling pollutants, the level of efficiency each is achieving, their capacity, and other characteristics are the bases for determining the extent and types of control methods needed to meet the selected standards. This information was derived from published data, trade association reports, and inter-

views with industry and Environmental Protection Agency contacts. Assumptions, including the set of control regulations, are identified in this report. Obviously the results in terms of emissions and control costs that are tabulated, depend on the underlying assumptions. If the assumptions hold, then the results as estimated will follow. In this report, 1970 was used as the base line year and coverage is for the entire United States. Control costs are estimated in terms of the initial investment required to establish control and the continuing annual expenses related to that investment. The investment cost is the total expense of purchasing and installing control equipment. The annual cost is the ultimate yearly charge for capital-related costs (interest on the investment funds, property taxes where applicable, insurance premiums, and depreciation charges) plus operating (labor, utilities, and supplies) and maintenance costs. In addition, this report presents estimates of the impact of industry costs both on the industries themselves and on the consumers of the products produced.

C. Report Organization

This report is organized with this, the OVERVIEW chapter, followed in order by chapters on ASBESTOS, BERYLLIUM, and MERCURY. The overview includes an introduction to and summary of the report. The summary follows, in general, the same format as the report. Asbestos mining and milling, asbestos handling, manufacturing asbestos-containing products, and sprayed asbestos-cement insulation are discussed in Chapter 2. Beryllium extraction and processing are discussed in Chapter 3. Mercury mining and smelting, secondary mercury, and mercury cell chlor-alkali production are discussed in Chapter 4. Major conclusions of the report can be found in the summary. Further and more detailed tabulations and narratives are found in the body of the report.

III. Summary

A. Asbestos

Asbestos emissions would be reduced to 409 tons under the proposed control measures from an estimated 6,382 tons in 1977 without control. The total investment required for plants in place in 1970 would be $5.7 million. By 1977 an additional investment of $2.3 million would be

required. The annualized cost would increase from approximately $1.7 million in 1970 to approximately $2.3 in 1977. As shown in Table 1-1, the major emission reduction would be by the asbestos milling industry. However, the highest cost would be incurred to reduce emissions from asbestos cement products and asbestos textile production.

Costs as indicated by this analysis do not appear to be large enough to have a major impact on the asbestos processing industries as a whole. Only in one case, asbestos textiles, are cost increases per unit of production more than one percent of sales price. The cost increase for asbestos textiles amounts to about 5 percent of sales price which is large enough to adversely affect the industry. Adverse effects are expected to be small, however, because of the specialized uses for asbestos textile.

Costs among plants are quite variable, and individual plants or companies may be adversely affected. It appears that such effects will be minimal.

B. Beryllium

The Atomic Energy Commission and the Department of Defense recognized the toxic nature of beryllium over 20 years ago. As the major purchasers of beryllium and beryllium products, they issued standards for permissible concentrations within the plants and surrounding communities of their suppliers. EPA proposes to adopt these same standards. As a result of these purchaser-enforced standards, emissions are adequately controlled by the major producers of beryllium, beryllium alloys, and beryllium ceramics. Therefore, no net costs are expected for controlling beryllium emissions, and no economic impact analysis is necessary.

Estimates of beryllium emissions are given in Table 1-1 for metal processing plants including primary producers, producers of beryllium alloys, and producers of beryllium ceramics. Emissions are estimated to be about 40 pounds per year for 1970 and are expected to increase to about 70 pounds per year in 1977 because of growth in the industry. No estimate of uncontrolled emissions is made for 1977 since emissions are currently controlled.

Table 1-1. ESTIMATED EMISSION LEVELS AND CONTROL COSTS FOR ASBESTOS, BERYLLIUM AND MERCURY

Source	Emissions (Tons)			Control Costs ($1,000)			
	1970	1977		Investment		Annualized	
		without control	with control	1970	1977 [1]	1970	1977 [2]
Asbestos							
Milling	3,860	5,440	218	$ 342	$ 139	$ 128	$ 180
Products							
Asbestos Cement	206	290	58	2,400	977	720	1,013
Floor Tile	101	142	28	216	88	65	91
Friction Material	314	441	88	720	293	216	304
Asbestos Paper	15	21	2	348	142	104	146
Asbestos Textiles	20	28	15	1,700	692	510	718
Sprayed Insulation	15	20	0	0	0	0	0
Sub-Totals	4,531	6,382	409	$5,726	$2,331	$1,743	$2,252
Berylliam							
Metal Processing	0.00562	[3]	0.0124	[3]	[3]	[3]	[3]
Alloys	0.00396	"	0.0072	"	"	"	"
Ceramics	0.011	"	0.0163	"	"	"	"
Sub-Totals	0.02058	"	0.0359	"	"	"	"
Mercury							
Roasting	50	50	.5	1,033	0	586.5	586.5
Secondary	0.03	0.04	0.004	5.6	.225	8.64	11.37
Chlor-Alkali	70	105	6.7	14,725	0	17,344	14,900
Sub-Totals	120.03	155.04	7.304	15,763.6	0.225	17,939.14	15,497.87

[1] Investment above that for 1970.

[2] Total for effects of the Clean Air Act and amendments.

[3] Current controls are adequate to meet the standards proposed, therefore, emissions without controls are not estimated for 1977 and additional investment and annualized costs are not required.

C. Mercury

The sources of mercury emissions to the atmosphere which have been analyzed for this project are primary mercury production plants (smelters associated with mines), secondary mercury recovery and refining plants, and plants using mercury chlor-alkali cells. As shown in Table 1-1, the 1970 total atmospheric emissions of mercury from these sources are estimated to be about 50 tons, 60 pounds, and 70 tons, respectively. By 1977 without controls, emissions are estimated to remain the same for primary mercury production, to increase to 80 pounds for secondary mercury recovery, and increase to 105 tons for chlor-alkali production using mercury cells. Controls would reduce these to 0.5 tons, 8 pounds, and 6.7 tons respectively.

The total investment required for plants in place in 1970 is estimated to be 15.8 million. By 1977 an additional investment of $0.2 million would be required. The annualized costs are estimated to be $17.9 million dollars in 1970 and decrease to $15.5 in 1977. Costs as indicated by this analysis are quite variable in their impact on the different sectors of the industry.

Primary mercury production will be very adversely affected by any costs imposed to control emissions. Product prices are already depressed below production costs and many primary producers are shutting down as a result. Factors depressing prices are increased world production, congressional hearings on the effects of mercury on man and the environment, cancellations of mercury biocide registrations, reduced consumption for chlor-alkali production and reduced consumption resulting from the general economic recession. No attempt was made to analyze the economic impact of pollution controls on mercury prices.

Estimated costs to control emissions for secondary mercury recovery and refining plants are minimal. Little or no adverse economic impact is expected.

While the portion of the chlor-alkali industry using mercury cells for production will have to invest almost $15 million to control emissions, the economic impact will not be large for the industry. Companies producing chlor-alkali are financially strong, and enjoy a market that has been increasing almost 7 percent a year. In addition, chlorine or caustic is only a minor cost in most products where they are used and substitutes are not readily available. Three-fourths of the companies making chlor-alkali operate both type of cells. Only one firm uses mercury cells exclusively and depends on chlor-alkali for the bulk of its sales.

The biggest competitive impact will be between the mercury cell process and the diaphragm cell process. In the past the mercury cell process appears to have had the competitive edge. It now appears that emission control costs will cause the diaphragm cell process to be economically more efficient.

Prices are expected to increase, but not by the full amount of the cost increase. Increases are estimated to be about $0.55 to $0.65 per ton which is approximately two-thirds of the unit cost of emission control for the industry.

CHAPTER 2

ASBESTOS

I. Introduction

Asbestos is a class of minerals which is extremely useful in a form which requires only mechanical processing. Chemically, the entire class is characterized as a naturally occurring fibrous silicate. Within this class are two subclasses: (1) Serpentine, or chrysotile, and (2) Amphiboles, including crocidolite, amosite, anthophyllite, tremolite, and actinolite. The properties of the asbestos are described in Table 2-1.

Commercially, chrysotile is by far the most important and most valuable of the asbestoses, especially in "spinning" grades of fibers (3/4" or longer). The properties which make asbestos useful are its long, extremely fine and flexible fibers, which are thermally, electrically, and chemically inert, of high tensile strength and of extremely favorable frictional properties.

The asbestos air pollution problem is related to the fact that asbestos fibers are a health hazard. This has been long recognized. Fibers may travel significant distances because of their fine structure and low density. Fibers are not destroyed by any known environmental process. The primary danger from asbestos is inhalation of the fibers into the lungs. The British Occupational Hygiene Society has found that fibers 200μ or less in length and 3.5μ or less in diameter are respirable [Reference 1]. Most asbestos fiber is less than 0.5μ in diameter. Virtually all asbestos fiber is therefore respirable [Reference 2].

It has been shown that hign incidences of lung cancer, pleural or peritoneal mesothelioma, and asbestosis[a/] are all strongly correlated with exposure to atmospheric asbestos. All these diseases may be fatal

---

a/ Asbestosis is an asbestos-induced disease closely related to coal miners' black lung and cotton workers' brown lung; pleural and peritoneal mesotheliomas are tumor-like hardenings of the rib cage and abdominal linings, respectively. In the case of lung cancer, it has been shown that asbestos exposure and smoking are synergistic by a factor of 8. (Selekof et al, 1968)

TABLE 2-1. CHEMICAL, MINERALOGICAL, AND PHYSICAL PROPERTIES OF THE DIFFERENT VARIETIES OF ASBESTOS FIBERS

Variety / Property	Chrysotile	Crocidolite	Amosite	Anthophyllite	Tremolite	Actinolite
Chemical formula	$3MgO2SiO_2 2H_2O$	$Na_2OFe_2O_3 3FeO_3 - 8SiO_2H_2O$	$1.5MgO5.5FeO - 8SiO_2H_2O$	$7MgO8SiO_2H_2O$	$2CaO5MgO - 8SiO_2H_2O$	$2CaO4MgOFeO - 8SiO_2H_2O$
Essential composition	Hydrous silicate of magnesia	Silicate of Na and Fe with some water	Silicate of Fe Mg higher iron than anthophyllite	Mg silicate with iron	Ca and Mg silicate with some water	Ca Mg Fe silicate; water up to 5 %
Percentage chemical composition						
SiO_2, %	37 -44	49 -53	49 -53	56 -58	51 -62	
MgO, %	39 -44	0 - 3	1 - 7	28 -34	0 -30	
FeO, %	0.0- 6.0	13 -20	34 -44	3 -12	1.5- 5.0	
Fe_2O_3, %	0.1- 5.0	17 -20	---	---	---	
Al_2O_3, %	0.2- 1.5	---	2 - 9	0.5- 1.5	1.0- 4.0	
H_2O, %	12.0-15.0	2.5- 4.5	2 - 5	1.0- 6.0	0 - 5.0	
CaO, %	Tr. - 5.0	---	---	---	0 -18	
Na_2O, %	---	4.0- 8.5	---	---	0 - 9	
CaO + Na_2O, %	---	---	0.5- 2.5	---	---	
pH	9.2-9.8	---	---	Neutral	---	---
Resistance to acids and alkalies	Poor	Good	Good	Very good	Good	Fair
Ionizable salts, micromhos (relative electrical conductance)	1.82	0.84	1.34	0.58	---	---
Magnetite content	0 -5.2	3.0-5.9	0	0	0	---
Mineral impurities present	Iron, chrome nicke., lime	Iron	Iron	Iron	Lime	Lime, iron
Crystal structure	Fibrous and asbestiform	Fibrous	Prismatic, lamellar to fibrous	Prismatic, lamellar to fibrous	Long and thin columnar to fibrous	Long and thin columnar to fibrous
Crystal system	Monoclinic and orthorhombic	Monoclinic	Monoclinic	Orthorhombic	Monoclinic	Monoclinic
Minearalogical structure	In veins of serpentine, etc.	Fibrous in iron stones	Lamellar, coarse to fine fibrous and asbestiform	Lamellar, fibrous asbestiform	Long, prismatic and fibrous aggregates	Reticulated long prismatic crystals and fibers
Mineral association	In altered peridotite adjacent to serpentine and limestone near contact with basic igneous rocks	Iron rich silicious argillite in quartzose	In crystalline schists, etc.	In crystalline schists and gneisses	In Mg limestones as alteration product of magnesian rocks, metamorphic and igneous rocks	In limestone and crystalline schists

TABLE 2-1 (Continued). CHEMICAL, MINERALOGICAL, AND PHYSICAL PROPERTIES OF THE DIFFERENT VARIETIES OF ASBESTOS FIBERS

Variety / Property	Chrysotile	Crocidolite	Amosite	Anthophyllite	Tremolite	Actinolite
Veining	Cross and slip fibers	Cross fiber	Cross fiber	Slip, mass fiber unoriented and interlacing	Slip or mass fiber	Slip or mass fiber
Color	Green, gray, amber to white	Blue	Gray, yellow to dark brown	Yellowish brown, grayish white	Gray-white, greenish, yellowish, bluish	Greenish
Texture	Fine, soft to harsh, also silky	Soft to harsh, but flexible	Harsh and coarse but somewhat pliable	Harsh; soft to friable	Harsh or friable	Harsh, brittle
Luster	Silky	Silky to dull	Vitreous, somewhat pearly	Vitreous to pearly	Silky	Silky
Hardness	2.5-4.0	4	5.5-6.0	5.5-6.0	5.5	6±
Flexibility	High	Good	Good	Poor	Poor	Poor
Spinnability	Very good	Fair	Fair	Poor	Poor	Poor
Tensile strength, lb/in.^{2}	80,000-100,000; 824,000 (max.)	100,000-300,000; 876,000 (max.)	16,000-90,000	4,000 and less	1,000-8,000	1,000 and less
Fusion point, °F	2770	2180	2550	2675	2400	2540
Specific heat, BTU/lb/°F	0.266	0.201	0.193	0.210	0.212	0.217
Electric charge	Positive	Negative	Negative	Negative	Negative	Negative
Filtration properties	Slow	Fast	Fast	Medium	Medium	Medium
Specific gravity	2.4 -2.6	3.2 -3.3	3.1 - 3.25	2.85-3.1	2.9 -3.2	3.0 -3.2
Cleavage	010 perfect	110 perfect	110 perfect	110 perfect	110 perfect	110 perfect
Optical properties	Biaxial positive, extinction parallel	Biaxial ± extinction inclined	Biaxial positive, extinction parallel	Biaxial positive, extinction parallel	Biaxial negative, extinction inclined	Biaxial negative, extinction inclined
Refractive index	1.50-1.55	1.7 pleochroic	1.64±	1.61±	1.61±	1.63± weakly pleochroic
Resistance to destruction by heat	Good. Brittle at high temperatures	Poor, fuses	Good. Brittle at high temperatures	Very good	Fair to good	---
Temperature at maximum ignition loss	1800	1200	1600-1800	1800	1800	---

Source: Reference 3.

once they become established. Asbestosis is not normally fatal if the exposure to asbestos is eliminated before extensive lung fibrosis develops. Asbestos is unique among the hazardous substances, however, in that it does not have an acute toxicity. Asbestosis, in particular, is associated with long-term, primarily high-level, exposures to asbestos fibers. However, there is no known exposure threshold below which there is zero probability of one or another of these diseases. A recent study of lung tissue from randomly selected autopsies of the general public indicates that asbestos bodies (enclosed asbestos fibers) may be found in the lungs of one-fourth to one-half the entire U.S. population [Reference 4].

Such widespread occurrence of asbestos fibers in human lungs very likely results from the varied uses for asbestos. Asbestos is used in over three thousand industrial and commercial products ranging from special-purpose textiles to vehicle brake linings. It is used as a filler in plastics, for filters in many industrial applications, and an essential ingredient in asbestos-cement pipe and sprayed asbestos-cement insulation.

Free asbestos is largely handled by air convergence during processing because of the need to protect the easily-broken fibers and its low density. Because asbestos easily becomes airborne, the air conveying system must be tightly controlled to recover the asbestos and protect the workers. However, because asbestos always contains large numbers of small, respirable fibers, this can be an exacting task in itself. Once the asbestos is mixed with a liquid medium (usually a binder or filler) there is essentially no further problem with emissions until the finishing process. If cutting, breaking, grinding, or polishing is required during the finishing process on an asbestos-containing material, there are usually dusty emissions present. There is no general agreement as to whether free asbestos is released in any particular case, and if not, whether there is any exposure potential involved. It will be assumed in the following discussion that these emissions must be controlled as though they are free asbestos emissions.

The next section of this chapter discusses the proposed emission standard, followed by sections on asbestos emission control techniques, the asbestos milling industry, asbestos processing industries, control costs, and economic impact of controls.

II. Control Standard

The asbestos control standard examined in this study is that all exhaust air from a plant or manufacturing facility which contains asbestos fibers must be passed through a fabric filter of appropriate design and adequate maintenance. There are several reasons for choice of this standard among which are the following:

1) Fabric filtration is the most effective and by far the most cost-effective method of asbestos emission control.
2) Fabric filtration is virtually the only high-efficiency control technique currently used by asbestos-using industries.
3) An emission-type standard is not possible due to the current lack of adequate emission monitoring techniques and equipment.

The control standard examined in this study differs from that described in a communication from the Hazardous Pollutants Branch, Environmental Protection Agency, July 3, 1972, which is as follows:

1) The national emission standard for asbestos:
   a) requires that emissions, in forced gas streams or as local visible emissions which are not presently ventilated, of particulate matter resulting from the milling of asbestos ore or the manufacture of products which contain commercial asbestos shall not exceed the amounts which would be emitted if these gas streams or local visible emissions were treated by a fabric filter or a wet collector which is adequately (specified) designed, operated, and maintained;
   b) allows certain processes (such as the printing of asbestos-paper-based flooring products), which involve bound asbestos and which do not release particulate matter which contains commercial asbestos, to be excluded from compliance with dust collection device requirements;
   c) prohibits the spraying, on a building or in an open area, of any product which contains asbestos (This is the prohibition as proposed December 7, 1971. The final version of the standard may allow the spraying of some products which contain small amounts of asbestos and/or products which contain bound asbestos);

d) prohibits visible emissions of particulate matter from external conveyors for asbestos-containing materials at asbestos mills;

e) prohibits visible emissions of particulate matter from any manufacturing process (of a product containing commercial asbestos) which is in an open area and which is not regulated by a specific collection device requirement;

f) prohibits the surfacing or resurfacing of any roadway with asbestos tailings except at asbestos mines and at asbestos mills which are located on property contiguous to asbestos mines;

g) prohibits the deposition of asbestos ore or asbestos-containing tailings into containers or vehicles intended for shipment of such materials on public roadways except in containers or vehicles which, when subsequently sealed, covered, or otherwise enclosed, prevent visible particulate emissions derived from asbestos ore or asbestos-containing tailings.

III. Control Techniques

As mentioned in the previous section, the only acceptable final control technique for asbestos from manufacturing process emissions in the proposed standard is use of a fabric filter. This will be the only technique discussed in detail. However, other techniques which have been used and are still being used for various reasons will be mentioned.

Collection by dry cyclone devices is very commonly used. However, they have low collection efficiency because of the fine size of many asbestos fibers (<1 micron diameter) coupled with their low specific gravity (~2-3). Dry cyclone are used because the asbestos that is collected, which may be a large fraction by weight of total process emissions, is generally either marketable or usable in the process. In fact, dry cyclones are essential process equipment in asbestos milling using air aspiration. In terms of emission control, however, dry cyclones are acceptable only as pre-cleaners to reduce fabric filter loadings.

Wet collecting equipment, such as wet cyclones or venturi scrubbers, are rarely used, since there are many problems associated with asbestos slurries. Pumps, drains, etc. tend to become clogged. It is difficult to reclaim reusable fibers from the water, a high removal efficiency is expensive to achieve in the venturi scrubber type system. Wet cyclones can capture asbestos fibers for reuse, but clogging and blinding problems generally arise in the baghouse that must follow the wet cyclone in order to meet the standard, due to the humidity resulting from wet collection. There are some applications for which wet collectors can provide collection performance comparable to that of fabric filters and some applications for which fabric filters cannot be utilized.

Electrostatic precipitators have been tried as asbestos collectors, but have proved to be inefficient collectors due to the resistivity characteristics of most asbestoses. Therefore, their expense is not justified.

Fabric filters have been found to be nearly ideal for asbestos emission control. Some reasons are:

1) Any asbestos fiber captured need not be further processed for reuse.

2) Once the fabric is coated with asbestos, the asbestos becomes its own, nearly "absolute" filter.
3) Baghouses provide collection efficiency equal to or better than any other collection system.
4) Baghouses cost less to buy, maintain, and operate than any system with comparable asbestos collection efficiency.

As a result, fabric filters are by far the most common type of high-efficiency control system currently in use on asbestos emissions. As an example of the efficiency of control of asbestos emissions by baghouses, it may be noted that cleaned air from these systems using cotton sateen bags are frequently recirculated into work areas, especially where accurate humidity and temperature control are necessary, or where savings in heating and cooling expenditures may be significant. It thus appears that baghouse emission control can meet or exceed the industrial hygiene TLV of 5 fiber/cm^3, where "fiber" is defined as an asbestos particle 5.0 μm or greater in length and with a 3:1 length to diameter ratio or larger [Reference 5]. This concentration of fibers corresponds roughly to 5 million particles per cubic foot (5 mppcf), when total particles are counted rather than fibers only.

Baghouse filters have both advantages and disadvantages as compared with other methods of collection. The prime advantages are:

1) It is a high-efficiency dry system, so that water treatment and water handling are not required.
2) Larger systems, in particular may be sectionalized, so that maintenance may be done on one section while the others continue to operate.
3) Collected materials may be returned directly to the process, unless they are too fine, when they may be used in some other application.
4) The baghouses will control other dry particulate emissions with equal facility if required.

Some of the principal disadvantages are:

1) Large installation area per unit gas flow.
2) Minor bag damage can cause significant loss in cleaning efficiency.

3) Cleaning efficiency is variable, being lowest just after bags are cleaned or new bags are installed.

4) Bag changing is expensive, both in labor and materials.

5) Baghouse temperature must be kept above the dewpoint but below bag tolerance limit, sometimes a delicate procedure.

It is clear from the wide use currently made of baghouses in controlling asbestos emissions that the positive factors significantly outweight the negative factors. Therefore, costs and emission calculated for this report, as shown in Table 2-2, are based on this method of control, except as noted.

TABLE 2-2. COSTS OF CONTROL AND RESULTING EMISSION CONTROLS FOR ASBESTOS EMISSION SOURCES (NATIONWIDE) (1970 Base)

Source	No. of Plants	PRODUCTION (Tons of Fiber) 1970	PRODUCTION (Tons of Fiber) 1977	EMISSIONS (Tons) 1970 W/O Control	EMISSIONS (Tons) 1977 W/O Control	EMISSIONS (Tons) 1977 With Control	CONTROL COSTS ($1,000) Investment 1970	CONTROL COSTS ($1,000) Investment 1977[1/]	CONTROL COSTS ($1,000) Annualized 1970	CONTROL COSTS ($1,000) Annualized 1977[2/]
Milling	9	125,314	176,300	3,860	5,440	218	$ 342	$ 139	$ 128	$ 180
Products										
Asbestos Cement	48	412,500	580,400	206	290	58	2,400	977	720	1,013
Floor Tile	18	201,200	283,100	101	142	28	216	88	65	91
Friction Material	30	104,600	147,200	314	441	88	720	293	216	304
Asbestos Paper	29	30,200	42,500	15	21	2	348	142	104	146
Asbestos Textiles	34	18,100	25,500	20	28	15	1,700	692	510	718
Sprayed Insulation	*	2,000	0	15	20	0	0	0	0	0
Totals	168	893,914	1,255,000	4,531	6,382	409	$5,726	$2,331	$1,743	$2,252

1/ Investment above that for 1970

2/ Total for effects of the Clean Air Act Amendments

IV. Asbestos Mining and Milling

A. Occurrence and Mining Techniques

Chrysotile (serpentine asbestos), which accounts for over 95% of U.S. production, occurs in three types of formations: cross fiber, slip fiber, and loose. Cross fiber chrysotile is that in which the fibers span gaps (veins) in the surrounding serpentine rock formations. Slip fiber occupies similar gaps in the formations, but the fibers lie parallel to the walls of the vein. Loose fibers, which occur at only one mine site in the U.S., are "pre-milled", occurring in loose formations near ground level mixed with various-sized aggregate. Cross fiber chrysotile is commercially most valuable, since the highly prized spinning length fibers (3/4" or longer) are most commonly found in such formations. (However, the longest known fiber bundle ever mined was from a Chinese slip fiber formation, and had a maximum fiber length of some 3 1/2 ft). Cross fiber and slip fiber may be mined by surface (open cast or open pit) techniques or by underground methods, while loose fiber is mined by what is essentially an open cast process.

Open cast mining involves removal of the ore by earth-moving equipment from shallow deposits, in one instance in the U.S. without the need for blasting. Generally, a shallow overburden with low concentrations of asbestos fibers must be removed. There will be emissions of asbestos fiber from the overburden dumps and exposed ores through weathering, and in concentrated amounts from drilling, blasting, overburden and ore removal, loading, and transport.

Open pit mining is similar to open cast operations except that the workings are much deeper to follow the fiber veins. Blasting and ore removal occur primarily on the sides of the pit along terraces which spiral down around the sides of the pit toward the bottom. Sources of emissions are the same as for open cast mining except that overburden removal will be proportionately smaller.

Underground mining of asbestos involves following the veins of ore with shafts, galleries, and drifts, using blasting and earth moving. However, there is no overburden removal, ore veins are not exposed to weathering, and many dusty operations take place underground. Therefore,

emissions from this type of asbestos mining are much lower than for surface mining techniques. There will be significant emissions from surface ore transfer and transportation and hand cobbing of ore.

A new method of mining which has particular significance in control of emissions from open pit mining is the block caving technique, which significantly reduces the required blasting and eliminates the need for overburden removal. When the volume of rock to be mined has been determined, that volume is undercut, leaving solid support pillars to hold up the main block. As the block caves in down the "chimney", ore is removed from underneath and mill and mine tailings are replaced on top to maintain the downward pressure on the block. Replacement of the tailings also reduces tailing dump emissions and space requirements. The block caving technique also reduces direct mining emissions to a level comparable to "normal" underground mining operations [Reference 11].

Transporting the ore from the mine to the mill generates emissions which are generally grouped with those of mining rather than milling. Such emissions arise in large measure from open trucks, which are typically 20 to 75 tons capacity, although some 200-ton units are in use. Private mine-mill roads are frequently paved with tailings, which liberate fibers to the environment as the trucks pass. In this context the use of 200-ton trucks has mixed significance for emission levels during transport. The larger truck capacity should reduce emissions from the transported ore, with their larger volume-to-surface ratio, and it reduces the number of trips per unit of ore. However, the road itself takes a bigger beating from each truck pass. The relative significance of the two effects has not been determined.

Mining of asbestos is limited in this country to the four states of California, Vermont, Arizona, and North Carolina. A small amount of anthophyllite is mined at two locations in North Carolina; all the other mines produce varying grades and types of chrysotile.

The four firms in Arizona produce a special low-magnetite cross fiber chrysotile commanding a premium for electrical applications. These firms mine asbestos at several sites using underground mining techniques.

The four mines in California use the open cast method. One of these mines is in ore area where geological action has broken up the deposit, so that little or no blasting is required. This mine has some of the richest ore in the world, being in places up to sixty percent asbestos. (The U.S. average ore content is four percent.)

The mine in Vermont is the oldest and largest asbestos mine in the U.S. Both slip fiber and cross fiber chrysotile is mined there using the open pit process. The Vermont deposit is part of the large deposits identified as the Canadian belt in southern and southwestern Quebec.

There is concern that the six Quebec mines may be sources of asbestos emissions that carry over into the United States, particularly into Vermont. Further consideration of these emissions, however, is beyond the scope of this report.

B. Control Techniques for Mining Operations

The standard asbestos control technique of baghouse collection has limited application to mining processes. Portable baghouse systems can be used with good effect during drilling operations prior to blasting, since this is a localized emission source. However, this is a minor source in terms of total emissions, and some sort of wet drilling technique might be just as effective and much less costly.

Emissions from blasting are virtually impossible to collect once they occur. Two techniques can be used to reduce generation of emissions to a minimum. First is use of blasting techniques and calculations of charge which produce the minimum breakage of rock required, so that the rock is not "blasted all over the landscape". Second, a technique developed in France, which uses plastic capsules of water to suppress blast dust, appears to be quite effective (twenty to eighty percent reduction in emissions) [Reference 5]. Plastic contamination of the ore which could not be removed by present milling methods may, however, be a problem in applying this technique to asbestos mining.

Control of dust generated during ore loading does not appear to be feasible and is not known to be practiced in any asbestos mining

operations. Dusts generated during transport may be controlled by (1) wetting the ore surface, (2) covering the truck body with canvas or a more rigid sealing cover, (3) wetting road surfaces where they are covered with tailings. Wetting the ore surface in the trucks bed is not known to be used. In hot, dry weather it would have to be done frequently to be effective during long trips to the mill. Canvas covers are currently being used at several sites. Wetting road surfaces is used in some places. Constant wetting of the surface with water is effective but causes slippery road surfaces and requires much labor and water. Wetting cannot be used in freezing weather. Good results have been obtained (in increasing order of effectiveness) with road oil, a ten to twenty-five percent water solution of liquid sulfonate, and emulsified asphalt. Where the ore body is utilized as a mine road chemical dust suppressants may cause unacceptable ore contamination.

It is expected that the overall control level from careful application of the best techniques would be about eighty percent of the potential road dust emissions.

C. Asbestos Milling Processes

1. Introduction

Once asbestos ore has been mined, the asbestos fibers must be separated from it. When the asbestos has been separated, it is graded on the basis of content of various lengths of fibers. In general, for a particular source of chrysotile, the larger percentage of longer length fibers in the final mix bring the higher prices. The most expensive grade of fiber is called "crude", which is not milled, but hand-separated ("cobbed") from the surrounding rock into bundles of fiber with aggregate fiber length of 3/4" or more. Crude (long) fiber is valued for weaving of asbestos textiles, for which shorter grades are not suitable.

In order to maintain maximum fiber length and promote maximum recovery, it is desirable to hold mechanical working of fibers to a minimum. Although asbestos fibers have very high tensile strength per unit area and per unit weight, the individual fibers are so fine that they are rather easily broken. Compounding the recovery problem is that asbestos fibers have the same

density and chemical composition as the surrounding rock. The solution applied in all but one of the asbestos mills in the U.S. is to use mechanical means to free the fibers from the rock, but accomplish the actual removal from the ore by an air aspiration system. In order to reduce fiber losses and industrial hygiene problems, it has become common to convey the fibers by air also. The result is a requirement for seven to ten tons of process air for every ton of fiber produced, or a volume ratio of about 1600 to one. The large volumes of air required, plus the "floatability" of asbestos fibers, leads to significant potential emissions.

The one exception to the air aspiration milling system in the U.S. is found in the mill which processes the loose fiber ore found in California. At this plant a proprietary wet separation process which presumably involves some sort of floatation technique is used to separate the fibers from the ore tailing. As a result, both industrial hygiene problems and air pollution potential from the fiber extraction process are significantly reduced.

The two milling processes and their corresponding emissions and control methods are discussed in the following sections.

2. Milling by Air Separation

The incoming ore is first unloaded from the arriving truck where a cloud of dust and fiber is generally produced. The incoming coarse ore is then typically crushed by a jaw crusher to a size that depends upon the mill. Oversize rock is separated by rotating cylindrical trammel screens and crushed in a secondary crusher, usually a cone type. The ore streams in most plants are then conveyed to a dryer (a rotary kiln in larger installations) where moisture in the ore (up to 30% by weight) is removed. The dried ore is then stored, with large amounts being held to allow for variations in fiber demand and mine production over time. At least one company departs from this procedure by storing the ore wet, thereby smoothing out drier operations and reducing emissions from ore storage and handling. This company further reduces emissions and "homogenizes" its

product by stripping ore for further milling from the underside of the storage pile via a moving conveyor systems housed in a tunnel chamber underneath the storage area.

Dried ore is conveyed to an additional crushing step and then through a series of milling, shaking, and aspirating steps. The milling, done by either hammer mills (fiberizers) or crushers, serves to separate the fibers from the rock and from each other. The shaking is accomplished on progressively finer screens, where small rocks and fiber bundles pass through for further treatment, larger rocks are retained for conveying to tailing dumps or further crushing, and the freed fibers are removed by air flow through powerful suction hoods.

Separated fibers are caught in dry cyclones and conveyed to grading screens. After grading, the fibers are sent to storage bins by grade (length). The final operations is removal of fibers from storage bins, blending in a mixer to produce the desired final grade, and bagging for shipment.

Residual rock, which contains a small amount of unremoved fiber and dust, is usually transported by some means to a tailing dump. If the block caving technique is used at the associated mine, the tailings may be returned to the mine to assist in the caving.

Every one of the processes described above leads to some loss of fibers to the air either inside or outside the plant. Emissions to in-plant air are usually kept to a minimum consistent with maintaining the industrial hygiene Threshold Limit Value. This is most effectively accomplished by operating as many pieces of equipment as possible in a closed condition and under a slightly negative pressure. This is done, however, at the expense of increasing the plant ventilation load and greater potential atmospheric emissions.

The major emissions potential at asbestos mills arises from the cyclone collector exhaust. The series of process cyclones normally used are of a relatively large-diameter design to limit damage to the fibers as much as possible. The resultant overall capture efficiency

for the series is in the range of ninety percent. The asbestos fibers which escape are predominately the smaller, respirable and wind transportable ones. The overall emissions by the asbestos milling industry, which has a partial usage of fabric filters, is 100 pounds per ton of asbestos produced, or a rate of loss of about five percent.

The source of emissions in the mill which is more expensive than the others to control is the ore dryer. The exhaust stream of the dryer is typically at high humidity and about 250°F. The associated baghouse must therefore be insulated to avoid condensation and resultant blinding, and the bags need to be of temperature-resistant materials, such as Orlon or Dacron. This means, in practice, a separate baghouse or baghouse section, and higher investment and maintenance costs than for other emission sources in the mill.

3. Milling by Wet Method

The details of operation of the one wet mill asbestos plant in the U. S. are not known, since it is a proprietary process. However, two important points relevant to emissions are known. First, because of the loose nature of the ore at the source of this mill's asbestos, little or no ore crushing is required. Second, the product is available as either loose fiber or as compressed pellets or balls of 1/4" - 1/2" diameter.

However, because of the nature of the ore more emissions are to be expected during transport and unloading, because so much more of the asbestos is free fiber at this stage. Emission potential during milling is virtually zero since the fibers are wet. Drying of the fiber, however, has great emission potential since the fiber is believed to be loose at this time. If the fibers are pelletized before drying, however, the emission potential would be comparable to that from conventional ore drying processes. Emission potentials from bagging and shipping of loose fiber would be the same as for conventional plants, but much less in the case of pelletized fiber. Emission from tailing dumps are expected to be less, especially if the

tailings are discarded wet, because of the low fraction or ore that becomes tailings. Water pollution potential, which cannot be discussed further, is of course quite high.

4. Emissions and Control Costs for Asbestos Milling

The estimated 1970 emissions and emissions after full controls are instituted are shown in Table 2-3 along with the associated control costs. There are two categories shown for control costs--"small" plants and "large" plants. This is done because the average control costs per ton of asbestos produced were fairly uniform within these categories, and because it was necessary to avoid identifying individual plants. However, such a classification does hide the variation in costs among plants. Additional control cost per ton varies among plants from zero to $5.96 per ton. The additional annual investment varies from zero to $183,000.

The control costs in Table 2-3 are based on a confidential plant examination describing the control equipment needed, and the data in Table 2-4. Minimum costs are assumed. Units are added rather than totally replaced, no land is acquired, and ducting is minimal. Table 2-5 estimates to cost of controlling emissions from asbestos milling for 1970 and 1977.

Table 2-3. EMISSIONS AND CONTROL COSTS ASSOCIATED WITH ASBESTOS MILLING (FOR PLANTS EXISTING IN 1970;1970 DOLLARS)

Plant Size	Number of Plants	Total Emissions 1970 Actual	Total Emissions If Fully Controlled	Control Costs Investment	Control Costs Annual	Per Ton of Capacity
Large	5	3,750	150	333,480	124,189	0.44
Small	4	110	4	8,340	3,579	1.38
Totals	9	3,860	154	341,820	128,189	0.78
Average		430	17	37,980	14,243	0.78

Table 2-4. UNIT COSTS FOR ASBESTOS MILLING EMISSION CONTROL

Control Unit	Investment (dollars/acfm)	Operating and Maintenance (dollars/acfm-year)
Cyclone collector	$0.55	$0.13
Baghouse		
Low temperature (cotton sateen bags, no insulation)	3.00	0.90
High temperature (Orlon bags, insulated)	6.00	1.30

Source: Reference 7

Table 2-5. COST ESTIMATES FOR CONTROLLING EMISSIONS FROM THE ASBESTOS MILLING INDUSTRY, 1970 AND 1977

Year	Estimated Capacity (Tons)	Required Investment	Annualized Cost
1970	163,600	$341,820	$128,189
1977	176,000	367,840	137,280

Gas flow data required to produce total costs for Table 2-3 from the unit costs in Table 2-4 were either obtained directly from an OAP/EPA survey of plant sites or were based on capacity data obtained in the survey combined with the seven tons of air per ton of asbestos criterion for air flows. The seven ton value is for milling only; air flows for drying of ore is highly dependent on ore asbestos concentration and water content. In any case, actual air flow rates for ore dryers needing control were directly available.

D. Economic Impact

1. Industry Structure

The asbestos milling industry in the United States is made up of nine plants owned by nine different firms. Four of these firms are large, vertically integrated firms that manufacture a wide range of asbestos and other products. These firms can use their total U.S. asbestos fiber production as raw material for further manufacturing into finished products for consumers and industry. The remaining five firms are much smaller and sell their production on the open market. The largest plants are not all controlled by the largest firms. Table 2-3 indicates the investment, the total annualized costs, and a cost per ton of fiber produced for the additional emission control equipment required by the industry. From the information currently available, it has not been possible to link individual plants with firms. This has limited the analysis of economic impact.

2. Production and Consumption

United States production of asbestos in 1970 was approximately 125,000 tons which was almost the same as the 1969 record high production. Domestic asbestos production has tripled since 1956, a pace that has been only slightly interrupted twice, and represents a rate of increase of about eight percent per year [Reference 1].

Domestic production normally supplies about 10 to 15 percent of United States consumption. The remainder is provided by imports, primarily from Canada, but with minor amounts from the Republic of South Africa and 10 other countries. Asbestos is traded in a world market where demand currently exceeds production at existing price levels (discussed below). As pressure on world supplies and price increases, expansion of domestic production can be expected to supply domestic buyers unable to obtain foreign supplies.

United States asbestos consumption decreased 17 percent from 1951 to 1961. From the 1961 low, consumption increased 31 percent to 875,000 tons in 1970. This represents a rate of increase of about three percent per year.

For this study, growth in domestic production was projected to be a five percent per year, which is about the growth in world consumption. It has been suggested that five percent is too high because production has been virtually level since 1966. Domestic asbestos consumption is tied to domestic construction activity which has been almost level until recently. As construction has increased asbestos consumption has increased.

3. Prices

Without yields by grades from asbestos ore, it is difficult to determine any kind of a realistic average price per ton of milled asbestos produced. However, the poorest grade was selling for $65-$90 per ton in Arizona (since August 1968) and the same grade $43.50-$90.50 per ton in Vermont (January 1970). Vermont prices were increased 4 to 12 percent depending on grade in 1969. Top grades sold for $386.50-$408.00 in Vermont and $1410-$1650 in Arizona. Although published Bureau of Mines data indicate that 125,314 tons of asbestos were sold in 1970 for $10,696,000, an average value of $85.35 per ton, it appears that this value is low. This value falls within the price range of the lowest grade. This may be because shipments made to plants within the same company are valued at cost rather than market value.

Prior to 1969, the world market for asbestos was a "buyers' market, but a signficant change to a "sellers" market has occurred since the end of 1969. All the South African producers are so fully committed that they are refusing to quote on substantial tonnages of chrysotile, crocidolite, and amosite. Demand exceeds present production capacity in the Western world and a shortage of asbestos fiber is occurring at current prices. Accelerated exploration, development and modernization of asbestos properties is occurring throughout the world to meet increased demand [Reference 9].

Prices for the various grades of chrysotile asbestos are set by the leading Canadian producers and are largely followed by chrysotile producers in the other parts of the world. Chrysotile prices have gradually increased over the years, keeping up with increasing production costs and other prices. The 1970 prices averaged about 30 percent above those in 1969.

4. Economies of Scale

Annual control costs of $5.96 per ton of fiber produced are indicated for some plants. It is believed these plants are almost completely uncontrolled, indicating that $6 is close to the maximum unit cost to control air pollution by asbestos plants.

Production information indicates that about 20 percent of the asbestos fiber from ore is caught in the baghouse by plants equipped with baghouses. Plants equipped with baghouses have been able to sell about half of their baghouse catch. While the price is relatively low for this grade of fiber, such sales can add about five percent to sales revenue [Reference 7]. Therefore, plants with sufficient baghouse catch to supply a market do realize some economy from their size. In total the economies of scale are not very large.

5. Price Impact

Since asbestos prices are set in the world market and U.S. production supplies only 10 to 20 percent of U.S. consumption, domestic plants could be expected to have little chance of passing increased costs along as price increases.

Exceptions would occur in case of certain fibers that are in short supply in world markets. Producers of these fibers could increase prices whether or not their production cost had increased. The bases for the ability to pass on such a price increase would be supply and demand factors rather than pollution control cost changes. It appears that Arizona chrysotile producers could increase prices on certain grades. Demand for Arizona filter fiber continues to be very strong and some grades are in short supply. This is expected to continue for the near future.

Available information indicates that the Arizona producers probably have the small plants faced with the high control costs. If this is true, the current strong market would certainly help pay those control costs.

6. Impact on Competition

Control costs of $1.69 per ton of fiber or less are indicated for some plants. These plants are believed to be already partially controlled and therefore already absorbing much of control costs. Uncontrolled plants are currently realizing some competitive advantage because of their avoidance of pollution control costs. Imposition of air pollution control regulations would eliminate such a competitive advantage.

7. Investment Impact

The firms in this industry should have no difficulty obtaining the capital required to install the necessary pollution control equipment. Six of these firms have annual sales in excess of $1,000,000. Four of these are large diversified firms. The three smaller firms have rather modest equipment requirements costing less than $3,000 installed and therefore should not have difficulty paying for control equipment from retained earnings or from loans.

V. Asbestos Handling

A. Occurrence and Control

One source of emissions which are best controlled at the mill, although they do not occur there, are those from storing and transporting bagged asbestos fiber. There are several types of bags currently used by asbestos mills, and they vary in the amounts of emission they permit. In addition, spillover of fibers that occurs during bagging, plus fibers that adhere to the surface of the bags, are also source of emissions.

The emission from bagged asbestos are the result of tearing or breaking of weak bags, or leakage through tears, seams, or permeable bags. The optimum solution, which is currently being pushed by the milling industry, may be bulk transport in sealed railraod cars with appropriate loading and unloading techniques to minimize losses. This technique would also reduce losses by eliminating bagging, unbagging, and bag disposal. Until the time this technique is generally adopted, however, the best solution appears to be use of specially-designed bags.

B. Cost of Control

Table 2-6 shows the costs of the various types of bags currently used to hold asbestos fibers. Of those listed, the coated, woven polyolefin-fiber bags are reported to be as good as any of the listed bags in terms of strength and impermeability, and they are clearly suited to the application. Furthermore, their cost is relatively low for a woven bag. Usage of these bags throughout the industry would result in a significant reduction of fiber loss.

In 1970, 2,600,000 bags were required to ship the asbestos fiber produced in the United States. The bags used cost an estimated $536,432. Use of coated, woven polyolefin bags would have cost $637,000, an increase in cost of $100,568 to the industry. This increased cost amounts to slightly less than $0.04 a bag or $0.80 per ton of asbestos fiber shipped.

Table 2-6. COST OF BAGS FOR SHIPPING ASBESTOS FIBER, 1970

Type of Bag (100 lbs. size)	Cost per 1000 Bags	Number Used, 1970 (Thousand)	Distribution (percent)	Total Cost (1970)
7 oz. Jute laminated	$336.00	234	9	$ 78,624
10 oz. Jute	290.00	130	5	37,700
7 oz. Jute	210.00	780	30	163,800
5-Ply Kraft paper	200.00	156	6	31,200
4-Ply Kraft paper	170.00	520	20	88,400
3-Ply Kraft paper	130.00	416	16	54,080
Woven Polyolefin(coated)	245.00	208	8	50,960
Other	203.00	156	6	31,668
Total		2,600	100%	$536,432

Source: Reference 3

Net cost to the industry would be even lower. Bags of coated, woven polyolefin would reduce shipping losses from broken bags. If the average price of the asbestos shipped was $80.00 a ton, one 100 lb. bag of asbestos is worth $4.00. Preventing the loss of one bag of asbestos would pay the additional cost of 100 bags. If the fiber shipped is of higher value than $80.00 per ton (and much of it is) the net savings could be substantial.

It is interesting to note (Table 2-6) that 14 percent of the bags now used cost more than polyolefin bags, and a total of 22 percent of the bags used are of equal or greater cost.

Disposal of polyolefin bags would probably be no more difficult than disposal of any other type bag. In fact, in the manufacturing of floor tile they can be used in the product, whereas other kinds of bags cannot.

In summary, it is believed that no net cost would accrue to the industry from using polyolefin bags. The savings might be substantial.

VI. Manufacture of Asbestos-Containing Products

A. Nature of the Products and Processes

Asbestos products includes an extremely broad and diverse group of items that contain significant amounts of asbestos fiber. It is estimated that 3,000 items fulfilling a broad range of industrial and consumer needs are among those in this group. They include asbestos cement products, floor tile, friction materials such as brake bands and clutch facings, asbestos paper, and asbestos textiles. Table 2-7 gives the breakdown of the major uses for 1968

Table 2-7. U. S. CONSUMPTION OF ASBESTOS, 1968

Product	Tons of Asbestos Used	Percent
Asbestos Cement Products Shingles, siding, flat sheets corrugated sheets, wall board	410,000	50.2
Floor Tile Vinyl and asphalt	200,000	24.5
Friction Materials	104,000	12.7
Asbestos Paper	30,000	3.7
Asbestos Textile	18,000	2.2
Molded Thermal Insulation	16,000	1.9
Sprayed Insulation	3,000	0.4
Miscellaneous	36,363	4.4
Total	817,363	100.0

Source: Reference 9

Although about 3000 different asbestos products are manufactured, they can be divided into two categories for asbestos emission potential. Either asbestos remains as essentially free fiber throughout the process and in the final product, or the asbestos is wetted or bound into a matrix at an early stage of processing. Production of asbestos textiles is the major manufacturing process in the first category. Virtually all other manufacturing processes fall into the second category.

1. Receiving, Handling, and Storage

The processes of interest which are common to the manufacture of all asbestos-containing products are receiving, handling, and storage of the (bagged) asbestos fiber, the removal of asbestos from the bags, and the opening or fluffing of the asbestos fibers prior to the other manufacturing operations. There is also a potential emission problem from the discarded bags, which inevitably have asbestos fibers clinging to them.

Receiving, handling, and storage of bagged fiber can best be controlled by use of the polyolefin bags described in the section on asbestos milling, along with adequate precautions for careful handling, and rotation of stocks to use the oldest bags first. It is not anticipated that such procedures will produce any significant direct costs to the manufacturer.

Prior to their actual entry into the final product, the asbestos fibers must be removed from their bags, usually fluffed or "willowed" to loosen them from their packed condition, and conveyed to the start of the process. The most direct method of control, unless an air method is used for fluffing the fibers, is to totally enclose the operations involved and operate the entire apparatus under a slight negative pressure, with the resultant airflow cleaned by a baghouse filter. Collected fiber from the baghouse would normally be returned without difficulty to the production process.

If air fluffing of some sort is used, the basic control strategy is the same. However, much higher air flows would be involved, and the baghouse catch would be significantly greater, perhaps requiring a dry cyclone precleaner.

In either case the clean and nearly total recovery of the fibers, along with reduced workspace fiber loads, should be of some advantage compared with no control; costs should be partially offset by fiber recovery, increased worker efficiency, and decreased maintenance and janitorial expenditures. Even approximate quantification of such savings is not possible at this time, however, and no attempt to include such offsets has been made in the control cost calculations.

Required controls for other manufacturing steps will be discussed with the descriptions of the individual processes studied for this report, which follow.

2. Asbestos Cement Products

Products in this category comprise the largest total volume of asbestos-containing materials and use the largest total amount of asbestos of any category (410,000 tons in 1968). Specific products include wallboard, pipe, shingle, and block, and dry mixture for sprayed insulation. Advantages of the products over their non-asbestos counterparts are improved tensile strength and strength-to-weight ratio, strength under heat stress and resistance, and smoothness of finished surfaces (critical in pipe to be used for liquid transport).

After the asbestos fiber has been prepared, it is mixed with the cement, as about 15%-20% of the total material, either wet or dry. If the mixing is done dry, the resulting mixture is generally metered in a flat layer onto an open surface where the requisite water is applied by overhead spray [Reference 3]. The resulting layer, much thinner than the final product, is then wound onto mandrels (for pipe) in a spiral mat until the requisite thickness is built up, or is layered flat onto wallboard or shingle forms, etc. The same winding or layering process may be used for wet-mixed products, or the mixture may be cast.

It is not known what advantages result from either the dry or wet mixing methods, except that the dry method obviously has higher emission potential. Once the mixture has been wetted, and through all other processes except finishing, emission potential for asbestos fiber is essentially zero.

Finishing processes on the dried cement products vary with product requirements and type and may include grinding, drilling. sawing, and cutting. All of these processes are dusty, although in varying degrees. It is not known whether any free asbestos fiber is released by these operations, but it is assumed that it is possible for some to be released, albeit a small amount in proportion to the total dust generated.

Collection of emissions from finishing processes would again be by baghouse. However, the hooding technique at these sources would be of high-velocity, low volume type as opposed to the low-velocity, high-volume type of system used for the fluffing and blending stages of processing. Furthermore, it is questionable that the collected material would be returnable to the process, since the fibers (if free) would be very short and the cement dust would be "spent" and useful only as aggregate. However, since the volume of collected material is so low, it would have very little effect on the properties of the finished product if it were recycled to the process. Its low volume means that, in any case, its reuse would have little if any economic value except to eliminate disposal requirements.

Control costs were based on the estimate that 95% of total potential emissions are currently controlled, some processes being fully controlled and others relatively uncontrolled. This was interpreted to mean that every plant, on the average, required a fabric filter and hooding system on its finishing processes, which are a small proportion of the total control requirements.

3. Asbestos Vinyl and Asphalt Floor Tile

Asbestos is used in vinyl and asphalt floor tiles because it improves strength and stability without reducing flexibility and compressibility. When used it comprises 10-30% of the total weight of the product.

Emission potential from floor tile manufacture, the second largest user of asbestos fibers, are nil as soon as the fibers are mixed with the hot vinyl or asphalt. The finishing processes involve cutting tiles to size and shredding wastage and trimmings

for reuse; emission of free asbestos fiber from finishing processes should be negligible because the cutting process does not disperse fibers into the air. Use of the polyolefin bags previously mentioned as a possible control of handling losses would eliminate any bag disposal problems, since these bags can be shredded and used as part of the material input.

Control cost estimates were based upon number of plants, average amount of asbestos used per plant, and the estimate that 95% of potential emissions are currently controlled on the average, some processes being completely controlled and some with lesser or zero control.

4. Asbestos Friction Products (Including Gaskets)

Friction products and gaskets using asbestos contain from 30% to 80% of asbestos in some sort of (generally) organic binder. In friction products the asbestos is used for its strength, frictional properties, and stability at high temperatures. Gasket materials do not depend upon the frictional advantages. The large usage of asbestos friction materials in vehicle brakes accounts for consumption of the third largest annual amount of asbestos of any product type.

Asbestos is used in these products in two different ways: (1) the asbestos, as loose fiber, is mixed with the binder; or (2) the asbestos, as either matted or woven textile, is impregnated with the binder. The low total volume of asbestos textile production indicates that the latter process is used only in special situations, probably in gaskets where dimensional stability is of significance. The further processes, such as molding, and curing, are pollution-free, at least with regard to asbestos. Shaping, cutting, sawing, and other finishing processes have at least some pollution potential, however.

Control costs were based upon number of plants, average amount of asbestos used per plant, and the estimate that 95% of potential emissions are currently controlled.

5. Asbestos Paper Products

Asbestos paper has essentially the same properties as normal (cellulose-based) paper, except that it has better thermal insulation properties and fire resistance. Its primary use is in insulation, although it has been reported that high-quality bond document papers are also produced, for durability and stability.

Asbestos papers are made by the same techniques as standard wood-pulp papers, but with the fiber being asbestos (80%-90%) and (typically) china clay and starch or sodium silicate being used as binders. Once the slurry is mixed in hollanders, emissions are nil until the final slitting process. It is expected that significant free fiber can be emitted during slitting, since the paper matrix is not as firmly formed as for other asbestos-containing products.

Control costs are based upon number of plants, average amount of asbestos used per plant, and the estimate that on the average, 95% of potential emissions are currently controlled. The implication derived from this is that one minor emission source, such as the slitting process, needs to be controlled.

6. Asbestos Textile Products

Asbestos is capable of being made into the full range of textile products, from nonwoven lap and felt through yarn and cord to woven cloth and tube, and braided rope and tube. However, the asbestos fibers required for textiles are significantly different from those used for other asbestos products, having to be quite long in order to be spinnable. This fiber is sometimes obtained in "crude" form as unopened, hand-cobbed, rock-free fiber blocks or bundles to protect fiber length.

If the fibers are received as crude, they are opened in edge (knife) mills into small, fiber-like bundles. These are then milled into extremely fine fiber for flexibility. This also makes the resultant fibers (a) more delicate and breakable, and (b) more "floatable", leading to a greater emission potential per weight of fiber.

Once the fibers have been adequately opened and fluffed, they may be blended with up to 20% of a cellulosic fiber such as cotton, the specific material chosen depending upon the application of the final product. The subsequent processes, such as carding, lapping, roving, spinning, and weaving or braiding (as required) are all performed on equipment essentially identical to standard textile machinery.

The key to the emission problem is that standard textile-type equipment and processes are used. This means two things: (1) large surface areas per unit volume of asbestos exist during the entire processing procedure; and (2) separate pieces of equipment that are impossible to hood for emission control, at least economically. This latter point results from the very large size of the machinery and the requirement for frequent access to the equipment.

Two recent developments in asbestos textile technology have positive implications for emission control. First, it has been found that a thin coating of a polymer on the asbestos yarn improves the processing efficiency; in general, the coating does not disturb the quality of the final product, and in some cases may enhance it. It also results in about 80% reduction in fiber emissions from processes following the coating process. Second, control of the processing environment (temperature, humidity, etc.), which has beneficial effects upon processing efficiency. Close environmental control is best and most economically handled by recirculation of the ventilation air required for industrial hygiene. Since this can only be done if the ventilation air is thoroughly cleaned, baghouse filters in the ventilation stream are used, resulting in high emission reduction. These procedures are not yet practiced on an industry-wide basis, however.

Costs of control are based upon total asbestos consumed, number of asbestos textile plants, and the estimate that 85% of potential emissions are currently controlled. 85% control was interpreted to mean that a major source of emissions is at present uncontrolled.

B. Economic Analysis

1. Industry Profile

The asbestos products industry (SIC 3292) includes establishments primarily engaged in manufacturing asbestos textiles, asbestos building materials except asbestos paper (industry 2661) and other products composed mostly of asbestos except asbestos gaskets and insulation (industry 3293).

In 1967 there were 139 asbestos products establishments (SIC 3292) employing 21,400 and shipping products valued at $576.5 million. The number of firms had increased 12 percent, the number of employees had increased 10 percent, and the value of products shipped had increased 13 percent since 1963. Value added by manufacture at $308.9 million in 1967 was 14 percent more than value added in 1963. These firms consumed 442,200 tons of crude fiber in 1967 which was 1,100 tons less than that consumed in 1963.

Asbestos paper (SIC 2661) is manufactured by 29 plants, with total shipments valued at $5.58 million. Normally, asbestos paper is 80-85 percent asbestos. This industry reported using 99,800 tons of asbestos worth $10.0 million in 1967.

The Gaskets, Packing, and Asbestos Insulations Industry (SIC 3293) includes establishments primarily engaged in manufacturing packing for air, steam, water, and other pipe joints, and for engines and air compressors; insulating materials for covering boilers and pipes; and gaskets. Establishment primarily manufacturing leather packing are classified in industry 3121, rubber packing in industry 3069, and metal packing in industry 3599.

In 1967, there were 300 establishments in this industry. This is only five more than in 1963 but 18 more than in 1958. The value of products shipped amounted to $350.8 million in 1967, an increase of 26 percent since 1963 and 86 percent since 1958. Value added by manufacture was $205.2 million in 1967, an increase of 28 percent above the value added in 1963. Employment increased 10 percent from 1963 to a total of 18,500 in 1967.

Value of asbestos, asbestos-metallic, and asbestos-rubber gaskets shipped totaled $62.3 million. Value of asbestos, asbestos-metallic, and asbestos-rubber packing shipped totaled $18.1 million. The value of insulating materials containing asbestos totaled $35.7 million. Manufacturers in this industry purchased crude asbestos at a delivered cost of $10.9 million in 1967. In 1963 they purchased 31,400 tons of crude asbestos worth $5.0 million [Reference 10].

2. Cost of Control

Table 2-8 shows the control costs for the major classes of the secondary asbestos products manufacturers. Total investment required is $5,384,000. The annualized cost is $1,615,200. This amounts to an average investment of 1.4 cents or an average annualized cost of 0.4 cents per dollar value of output. The annualized cost per dollar value of output ranges from 0.1 cents to 5.2 cents.

Service life for control equipment was assumed to be 10 years. Operations and maintenance cost were calculated at 10 percent of investment. Interest, insurance and taxes were also calculated at 10 percent of investment.

Table 2-8. ASBESTOS PRODUCTS INDUSTRY CONTROL COSTS, 1970

Product Group	No. of Plants	Value of Product (Million Dollars)	Investment ($1,000)	Annualized cost (1,000)	Industry Cost Annualized Cost To Value of Product Ratio
Asbestos Cement	48	$142,680	$2,400	720.0	.005
Floor Tile	18	37,200	216	64.8	.002
Friction Material	30	202,800	720	216.0	.001
Asbestos Paper	29	5,580	348	104.4	.002
Asbestos Textiles	34	9,900	1,700	510.0	.052
Total	159	$398,160	5,384	1,615.2	.004

3. Price Impact

As indicated in Table 2-8, the price increase to consumers, if all costs are passed on in increased prices, is significant for only one class of products--asbestos textiles. The price increase for that product group would be 5.2 percent. This would cause the loss of some sales, but such losses would be relatively small because of the specialized nature of the applications of asbestos textiles. The exact amount of this reduction in sales was not determinable from the data available in this study.

4. Investment Impact

The average plant investment required for control equipment and the average value of plant production is given in Table 2-9. In addition, the Investment to the Value of Product Ratio is given. This shows the investment burden is not very large, averaging less than one percent of sales for plants making floor tile and friction materials and less than two percent for plants making asbestos cement products. For these firms the required investment should be no problem except for firms that are already marginal.

For plants making asbestos paper and textiles, the required investment is 6.2 percent and 17.2 percent of product value respectively for the average plant. These are significant. In both groups one could expect the smaller firms to have difficulty obtaining the required capital and closures and consolidations may result. Data was, however, inadequate to determine the probable number of firms that would close.

Table 2-9. PLANT VALUE OF PRODUCT AND INVESTMENT OF THE ASBESTOS PRODUCTS INDUSTRY

Product Group	Value of Product Per Plant	Required Investment	Investment to Value of Product Ratio
Asbestos Cement	$2,972,500	50,000	0.017
Floor Tile	2,066,700	12,000	0.006
Friction Material	6,760,000	24,000	0.004
Asbestos Paper	192,400	12,000	0.062
Asbestos Textiles	291,200	50,000	0.172

VII. Sprayed Asbestos Fireproofing and Insulation

A. Nature of the Product and Process

Asbestos-cement insulation is applied to steel-frame buildings as thermal insulation and fireproofing; it also has good acoustic insulation properties. The sprayed mixture is approximately 30% asbestos, 55% rock wool, and 15% cement with sufficient water for mixing and setting. The dry mixture is delivered to site in 50-lb. bags. The spraying technique uses either a wet slurry pumped to a nozzle or a special nozzle which mixes water and the dry mix. Although small amounts of asbestos are emitted from this use, it is of significant concern because of its concentration in urban areas. Emissions of asbestos in this process arise from handling of the dry mixture, escape of unwetted fiber and mixture, overspray and backsplash, and cleanup and disposal of wastes.

There are various measures of partial control such as premixing with water in the bag, enclosing the sprayed area, and better cleanup and disposal control. Of course banning of the use of asbestos leads to total control. There are alternative materials such as mineral wool, ceramic fibers, calcium silicate and vermiculite alumina available for various applications which yield comparable results at a modest increase in cost. When it is considered that materials cost is low for the total cost of application of insulation, and that insulation is a minor expense in total construction, the impact is not significant. In fact, it is cheaper to use a different material than to apply the other techniques.

Sprayed asbestos insulation is not a major use of asbestos. Three thousand tons of asbestos were used in this product in 1968. Total consumption of asbestos was 817,363 tons that same year. Sprayed asbestos insulation was less than 0.4 percent of total consumption. The loss of sales of 3,000 tons would not have a major impact on either prices or the firms producing or marketing asbestos.

ASBESTOS REFERENCES

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Chapter 3: Beryllium

I. INTRODUCTION

The purpose of this chapter is to present the engineering analysis of air pollution controls for the industry sources producing or processing beryllium or beryllium containing materials. An economic discussion is not included because the engineering analysis indicates that all potential sources of beryllium emissions are controlled within the limits of the standards proposed at the time this study was concluded.

The primary producers of beryllium are represented under Standard Industrial Classification (SIC) Code 3339, and include those plants that produce beryllium metal, beryllium alloys, and beryllium ceramic intermediate materials and finished products to other industries or customers. The manufacturing industries are classified under SIC Code 2819 and 3369, and include some 5,000 fabrication plants and machine shops that are supplied beryllium metal, beryllium alloys, and beryllium ceramic materials by the primary producers for further conversion to finished products.

II. INDUSTRY PROFILE

There are two primary beryllium producers [Reference 2,3,4] and each uses one or more of three production processes: fluoride, sulfate, and acid-leaching, organophosphate extraction. The various steps in the production process are:

- Beryl or bertrandite ores to hydroxide
- Hydroxide to beryllium metal billets
- Billets plus scrap to beryllium metal shapes
- Hydroxide to beryllium plus scrap to alloy
- Hydroxide to ceramic intermediate powders and shapes

The process steps, except from ores to beryllium hydroxide, are very similar in the plants of the two primary producers. These primary production plants also manufacture the following general categories of products:

- Beryllium metal (billets, powders, pressed blocks, mill products and fabricated products)
- Beryllia (powders, ceramic shapes and waves and fabricated products)
- Alloys (cast billets, mill products, and fabricated products)

Beryllium metal products are made mostly from pressed powder and are forged, extruded, and machined. Beryllia powders are pressed, extruded, fired, and machined by ordinary ceramic techniques. Finished beryllium-copper alloy products are made from melts of copper and a master copper alloy containing 4% beryllium. Small quantities of beryllium-nickel and beryllium-aluminum alloys are also produced. Alloy products take the form of bar, plate, rod, wire, forgings, and billets.

Beryllium production in 1970 was about 394 tons *[Reference 2,3]. Table 3-1 presents the tonnage of beryllium found in the various beryllium-contained products produced by the primary production plants. These amounts of beryllium equivalent by type product are considered as inputs to the various manufacturing plants.

TABLE 3-1. Beryllium Production by the Primary Producers, 1970*

Product Type	Equivalent Be (short tons)
Beryllium Billets (Metal)	147
Master Alloy	225
Beryllium Oxide	22

* Exact production figures are not published in order to avoid disclosure of the activities of individual firms. The estimates used in this report appeared to be the most accurate available at the time. Production has declined in recent years, however, and it may be that these figures are significantly high.

III. TECHNICAL ANALYSIS

A. Nature of Product and Processes

1. Primary Producers(Be)

Beryllium has exceptional strength and rigidity, exceeding that of other metals including steels. It has a high strength-weight ratio and important thermal and nuclear properties.

Beryl (beryllium ore) is normally recovered as a co-product or by-product from mining of other minerals. Blasted rock is hand-cobbed and barren rock is broken off with hammers and discarded. Beryl and other valuable minerals are recovered at this time.

Several methods for converting beryl to beryllium oxide (BeO) have been developed. These production process methods are fluoride, sulfate and acid-leaching, organophosphate-extraction.

A brief description of each of the three production processes follows as well as a description of the processing required to produce beryllium metal.

Fluoride Process

Beryl containing 10-12 percent BeO is crushed, ground in a wet ball mill and filtered. It is then mixed in batches with soda ash, sodium silicofluoride, and sodium ferric fluoride and made into briquets. These briquets are dried, sintered at 750°C, cooled, crushed, and ground in a wet pebble mill to which hot water is added, and the slurry is pumped to a tank for leaching. More water is added and the mixture agitated, leached, and allowed to settle. The liquid, containing soluble sodium beryllium fluoride, is decanted to separate it from solids, which contain aluminum and iron oxides and silica. Caustic soda is added to the heated solution to precipitate beryllium hydroxide, which is filtered and calcined to convert it to beryllia.

Sulfate Process

Beryl containing 10-12 percent beryllia is crushed, dried, and melted at 1600°C in an electric arc furnace. The melted beryl is then quenched in cold water to obtain a frit, which is dried and ground to a fine powder. Batches of powder are mixed with

concentrated sulfuric acid, steamed and agitated. Water and more steam are added to the slurry. The liquid, containing soluble beryllium and aluminum sulfates is filtered from the sediment and pumped to a tank where ammonium hydroxide is added. The filtrate from this operation is further treated with a chelating agent to prevent impurities from precipitating upon subsequent addition of caustic soda. Hydrolysis follows, and the precipitate, beryllium hydroxide, is filtered off. This precipitate is ignited in an electric furnace to form beryllium oxide.

Acid-Leaching, Organophosphate-Extraction

Bertrandite from the Spor Mountain, Utah, mine is the first significant nonberyl source of beryllium (averaging 0.5 percent Be, but containing 17 percent moisture and creating little dust). It is mechanically removed from the mine without blasting and stockpiled. The ore is hydrated bertrandite and berylliferous saponite, found in association with the fluoride; the bertrandite is soluble in concentrated acids. The ore is first crushed in a jaw crusher that is hooded and the dusts evacuated for scrubbing. It is next slurried in water and pulverized in a ball mill. The sized slurry goes to process and rejects are recycled. The slurry is next acidulated with sulfuric acid which converts the Be to the sulfate. The calcium in the rock is converted to gypsum and then by pH adjustment, most unwanted solids are precipitated. The Be values remain in the weak mother-liquor which goes to further processing. An extensive counter current in the slurry settling system is employed that receives various recovery and scrubbing streams.

The process used by one of the primary producer plants is proprietary. The extraction system is basically an organic process that yields a wet cake product of beryllium hydroxide. The wet cake is fed into fifty-five gallon drums and shipped to another plant. All processing is totally enclosed, including vacuum stages, and vents are scrubbed so that stack emissions are not visible. As the drums are filled, they are tightly

enclosed and air evacuated through a scrubber. The highest temperature involved is 205°C. Accidental spills of powder or slurry are hosed down into a chemical sewer system that is flushed back to the slurry system. Standard emission control systems are being used. Exhaust streams are treated with wet venturi type scrubbers. Flow rates are controlled and exit gases monitored.

Processing to Beryllium Metal

After beryllium hydroxide is isolated in satisfactory form and purity, the processes are all rather similar in the operations of the major producers. In general, the fluoride process produces a technical grade beryllium oxide lower in aluminum and iron, while beryllium oxide from the sulfate process is lower in silicon and sodium. Both oxides are pure enough for production of commercial beryllium alloys. Nuclear grade beryllium metal, metal for space application, and shapes for nuclear and electronic industries necessitate the production of high purity grades of beryllium oxide.

The oxide or hydroxide can be dissolved in ammonium bifluoride solution and heated to boiling, and calcium carbonate flour added to precipitate aluminum. The solution formed is purified by precipitation and filtration, and the pure filtrate is evaporated and crystallized to produce pure crystals of ammonium beryllium fluoride. Next, the ammonium fluoride is driven off by heating, leaving a residue of beryllium fluoride. Decomposition is carried out in a graphite-lined furnace at a high temperature (900° to 950°C). The ammonium fluoride, which sublimes off at lower temperatures, is collected in an air-cooled iron condenser and recycled.

The solid beryllium metal produced by this process can be used directly as virgin metal for alloying purposes and for casting pure beryllium. The metal is remelted for casting purposes to remove any slag inclusions. The remelting process is carried out in a vacuum, without using fluxes, or at atmospheric pressure using a flux rich in beryllium fluoride.

2. Manufacturing Industries Using Beryllium

a. General

Manufacturing plants may be categorized as metal, alloy, and ceramic. The number of plants in each category is not known. Estimates range in the "hundreds" of metal plants, 5,000 to 7,000 alloy plants and something less than 100 ceramic plants. It has also been estimated that "hundreds" of foundries use beryllium alloys [Reference 3,4] and that some use the master (4%) copper alloy.* In determining control costs these estimates of the number of manufacturing plants are not meaningful. Model plants, however, can be established and control costs estimated for such plants. In all probability the degree of control of emissions varies from zero to full control (0.01 $\mu g/m^3$) within each plant category. Undoubtedly emissions from melting, pouring, and casting of beryllium alloys go uncontrolled in "hundreds" of these plants.

The operations in manufacturing plants are widely varying in type and amount. Shops using lathes, milling machines, and similar machinery may generate, as an example, an average of 0.05 to 0.1 grams per minute of beryllium dust; and this dust may be drawn off with 1,000 to 4,000 cfm of air with a source concentration of about $10^3 \mu g/m^3$. Alloys produce less beryllium dust per machining operation but are frequently subjected to foundry practices.

In a machining operation (e.g., lathes) a local exhaust pick-up of dust can be applied at the tool at 1,000 to 1,500 ft/min and the volumetric flow may be about 50 cfm depending on the inlet area of the pick-up. A grinding operation may require a plastic enclosure and a somewhat higher volumetric flow. A hood may be used for grinding or spraying operation and this may require 500 cfm at a face velocity of 150 ft/min. A foundry operation may require an exhaust of 5,000 cfm. From this it can be seen that the volumetric flow requirements for a manufacturing plant are generally less than 20,000 cfm.

Small companies may work Be metal and perform turning, cutting, drilling, milling and other operations, from which the total exhaust through manifold local pick-ups may be less than 1,000 cfm.

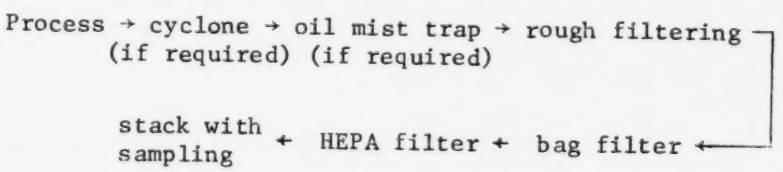
* EPA has estimated that approximately 90 percent of this production is concentrated in about 15 companies.

In such cases, a suitable package may be a mechanical (dry) collector, together with a pre-filter and a HEPA filter all in series to a stack. The collector system may have a resistance less than 10 in w.g. It is reported that HEPA filters have an efficiency rating of 99.9% for particle size of maximum leakage of 0.3 microns.

From all reports it appears that the control of emissions is thorough among government contractors but is highly variable in private industry.

Many companies apparently believe that since they use only a small amount of beryllium in various forms, controls are not really necessary. Also, there appears to be a belief, possibly erroneous, on the part of many users that "high fired" BeO is safe and consequently controls range from zero to full.

An example of full control cited by one report [Reference 3] is as follows:



b. Beryllium Metal Fabrication

Beryllium metal has unusual physical properties--high stiffness, high heat capacity, and low density. It is produced largely by reduction of beryllium fluoride with metallic magnesium. Beryllium metal is generally purchased as rod, bar, or billet. It is used in nuclear reactors as a moderator and reflector material. Other uses include gyroscopes, accelerometers, internal guidance systems, parts for high-speed flight and marine navigation, rocket propellant fuel, airplane brakes, and heat shield for space capsules. More recent uses include rotary blades and other parts for gas turbine engines, solar cell mounting boards for satellites, mirrors, portable X-ray tubes,

optical parts, X-ray diffraction and microradiography. Fabrication operations include turning, milling, drilling, reaming, grinding, honing, sawing, and abrasive cutting. Chemical and electrochemical procedures are also used. Review of reports indicate that about 147 short tons of the beryllium metal were produced for these uses in 1969 and that these figures included reclaimed scrap.

The number of machine shops that work Be metal is not known but is reported to be in the "hundreds" [Reference 3,4]. It is also reported that these shops have emission controls from zero to approximately 100 percent. It is estimated that in 1969, 127 tons of Be billets were produced from $be(OH)_2$. It is further estimated that the beryllium emissions from machine shops are 8 grams/day and it is assumed that these plants operate 250 days/year [Reference 3]. Based on these estimates and assumptions the emission factor (EF) would be:

$$EF = \frac{8}{\frac{127}{250}} = \frac{8}{0.508} = 15.75 \text{ grams/ton or } 0.035 \text{ lbs/ton .}$$

Be billets plus scrap to metal shapes were reported as 147 tons produced for 1969. The emissions are estimated as being 9 grams/day. Therefore:

$$EF = \frac{9}{\frac{147}{250}} = \frac{9}{0.588} = 15.31 \text{ grams/ton or } 0.038 \text{ lbs/ton.}$$

Ninety-five percent of all Be metal applications is for the government. One-half of this Be metal is used in nuclear weapon applications and the other half in noncommercial reactors. The estimated demand for Be metal by 1972 (using 1967 as a base) is 175%. This indicates a growth rate of about 12%. In 1970 Be metal was selling, on the average, for about $95.00 per lb.

c. Beryllium Alloys

To make beryllium-copper master alloy (4% Be) weighed quantities of BeO, carbon powder, and copper are mixed in batches and melted in an electric arc furnace. The product is impure beryllium-copper. Additional refining or other treatment removes the carbon and gases absorbed during reduction.

Beryllium-copper has high electrical and thermal conductivity coupled with strength and resistance to fatigue at high temperatures. Beryllium copper is used in springs, bellows, diaphragms, electrical contacts, aircraft enginer parts, bushings, valves, shims, pressure gauges, plastic molds, marine propellers, gears, bearings, precision castings, rollers, low-sparking tools, radio and radar devices. The largest users of beryllium-copper are in the electrical and electronic fields. Beryllium-copper is available in wrought, cast, or forged form. Most plants using beryllium-copper do not remelt or make basic changes in the alloy. The processing generally involves stamping or drawing into finished shapes.

Beryllium-nickel alloys are heat treatable and resemble stainless steels in many respects. Uses of beryllium-nickel alloys include surgical instruments, matrix for diamond drill bits, parts for fuel pumps and business machines, and dies for shaping aluminum channels, necks of bottles, stainless steel dinnerware, and plastics.

Beryllium confers to zinc-base alloys reduced creep, increased tensile strength, and improved corrosion resistance. Beryllium-zinc is identical with cold-rolled 70-30 brass in strength properties.

Beryllium-aluminum, ticonium, beryllium platinum, beryllium-steel, and beryllium salts are also available. None of these alloys, however, has a commercial demand.

Reports reviewed indicate that approximately 225 short tons of beryllium were used in 1970 in producing beryllium alloys and salts.

The emission factor computed below assumes that a plant is emitting 13 grams/day and that the plant operates 250 days/year in processing $Be(OH)_2$ to BeO, adding scrap, and producing beryllium alloys [Reference 3]. Therefore,

$$EF = \frac{13}{\frac{225}{250}} = \frac{13}{0.19} = 14.40 \text{ grams/ton or } 0.032 \text{ lb/ton.}$$

The National Resources Council indicates that the growth rate in the use of beryllium alloys (using 1967 as a base year) is about 5-15%/year.

d. Beryllia Ceramics

One of the best refractory materials known is beryllia. It has high thermal conductivity, high electrical resistivity, high melting point, and can be fabricated by normal ceramic processes. In the fabrication process, toxic beryllium oxide dust or fume may be inhaled. Also the machining of ceramic parts creates dust. Except for dust from breakage, finished ceramic articles can be stored without much danger of emissions.

According to one report a method used in producing beryllia ceramic commences with BeO and other materials which are batched in a large floor cistern containing water. After milling, wet screening, and adjustments, a glaze is applied to the unfired porcelain. The glaze becomes permanently fuzed to the ceramic article when fired. The glaze contains about 2% Be.

Beryllia ceramics are used in high-voltage electrical porcelains, suspension insulators, spark plugs, and microwave windows. BeO is used as a component in special glass for high speed transmission of light and as a liner in high temperature electric furnaces and rocket combustion chambers.

The number of ceramic plants using beryllium is reported [Reference 3,4] to be "less than a hundred".* There are five major beryllia ceramac plants. It is reported that these major plants use HEPA filters to control emissions.

About 22 tons of beryllium were used in 1969 in beryllia ceramics. The emission factor was reported as being 454 grams of Be or one pound per ton of beryllium processed [Reference 2,3].

e. Propellants

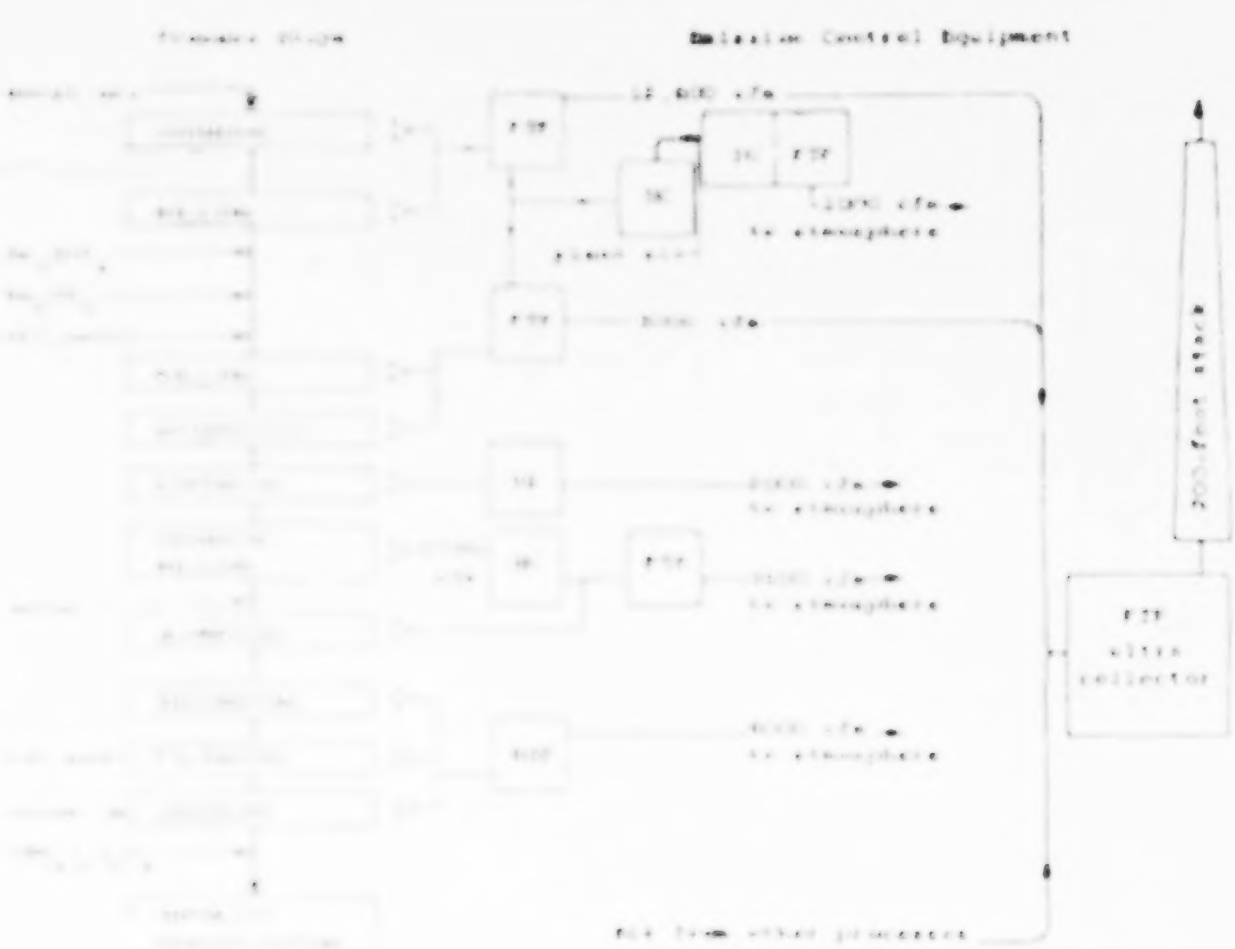
In the manufacture of beryllium solid rocket fuels, the beryllium used is normally received in powder form in polyethylene containers packed in steel drums. The beryllium powder is mixed with other materials in a dough mixer, vacuum cast, cured, and machined into final shapes. During the handling of the dry BeO

* EPA estimates that approximately 5 companies account for almost all activity in this field.

powder and during the machining operation emissions occur. The present degree of control of the emissions in propellant fabrication plants is reported as "high" with only 1 or 2 operations that are active. An estimated maximum of 1,000 pounds of beryllium is used in propellants--most of this is for the High Energy Upper Stage (HEUS) rocket motors which are tested outside the U.S.--each test requiring about 300 to 400 pounds of beryllium. Essentially, the emission controls used are the same type used in manufacturing beryllium containing products.

The present controls of exhaust gas in static firings are scrubbing for intermediate size grains and absolute filtration for very small grains. This method of control is questionable. Arguments have been put forth that the toxicity of BeO when "high-fired" is reduced to a safe level. This argument appears to lack creditability as there is no known practical way to distinguish high-fired oxide from low-fired oxide in the exhausts of experimental motors. Presently the DOD policy is to conform with DHEW Public Health Service policy which is as follows: In the event that the national defense requires planned, limited emissions of beryllium combustion products to the atmosphere prior to the availability of containment systems, the emission sites should be remote from places of human habitation and should conform with the following criteria: For intermittment exposure of off-site human population to any compounds of beryllium, the maximum exposure of 75 mg/min Be/m^3 of air may be tolerated with the limits of 10 to 60 minutes, accumulated during any 2 consecutive weeks.

Reports reviewed indicate that there were approximately ten facilities throughout the U.S. at which static firings of beryllium-enriched motors have been conducted. Most of these facilities have no beryllium motor static firing activity at the present time. One company at Bacchus, Utah, currently engages in beryllium-rich rocket grain fabrication.



FTF - fabric tube filter

DC - dry cyclone

VS - venturi scrubber

HST - hydraulic scrubbing tower

Figure 3-2

TABLE 3-3. AIR CLEANER COSTS#: FLUORIDE PROCESS, ORE TO $Be(OH)_2$

Class	Type*	Air ** Flow Rate	Maintenance Cost/Yr	Power *** Cost/Yr	Installed Cost	Annual Operating Cost
FTF	Reverse Jet	12,600 cfm	$1,200	$2,100	$25,400	$3,300
DC	High Efficiency	750	25	65	2,310	90
DC:FTF	Combined; conveying	1,000	130	1,240	6,910	1,370
FTF	Reverse Jet	5,000	475	940	10,700	1,415
VS	High Energy	2,000	155	2,500	13,860	2,655
DC	High Efficiency	2,700	80	220	3,455	300
FTF	Pulse Jet	3,900	355	470	10,700	825
HST	Med. High Energy	6,000	215	1,720	23,040	1,935
			2,635	9,255	96,375	11,890
**** 1/3 FTF	Shaker	1/3 x 65,000	2,040	2,730	26,900	4,770

* Among wet collectors, FTS and HST are here considered medium high energy types--FTS because of its 0.5-1.0 in. w.g. pressure drop per ft height, and HST because of pumping power requirements.

** Actual flow rates. Rated flow rates may be as much as 30% higher. Rated flow rates, where known, are used for installed cost estimate.

*** Makeup water is included in power cost.

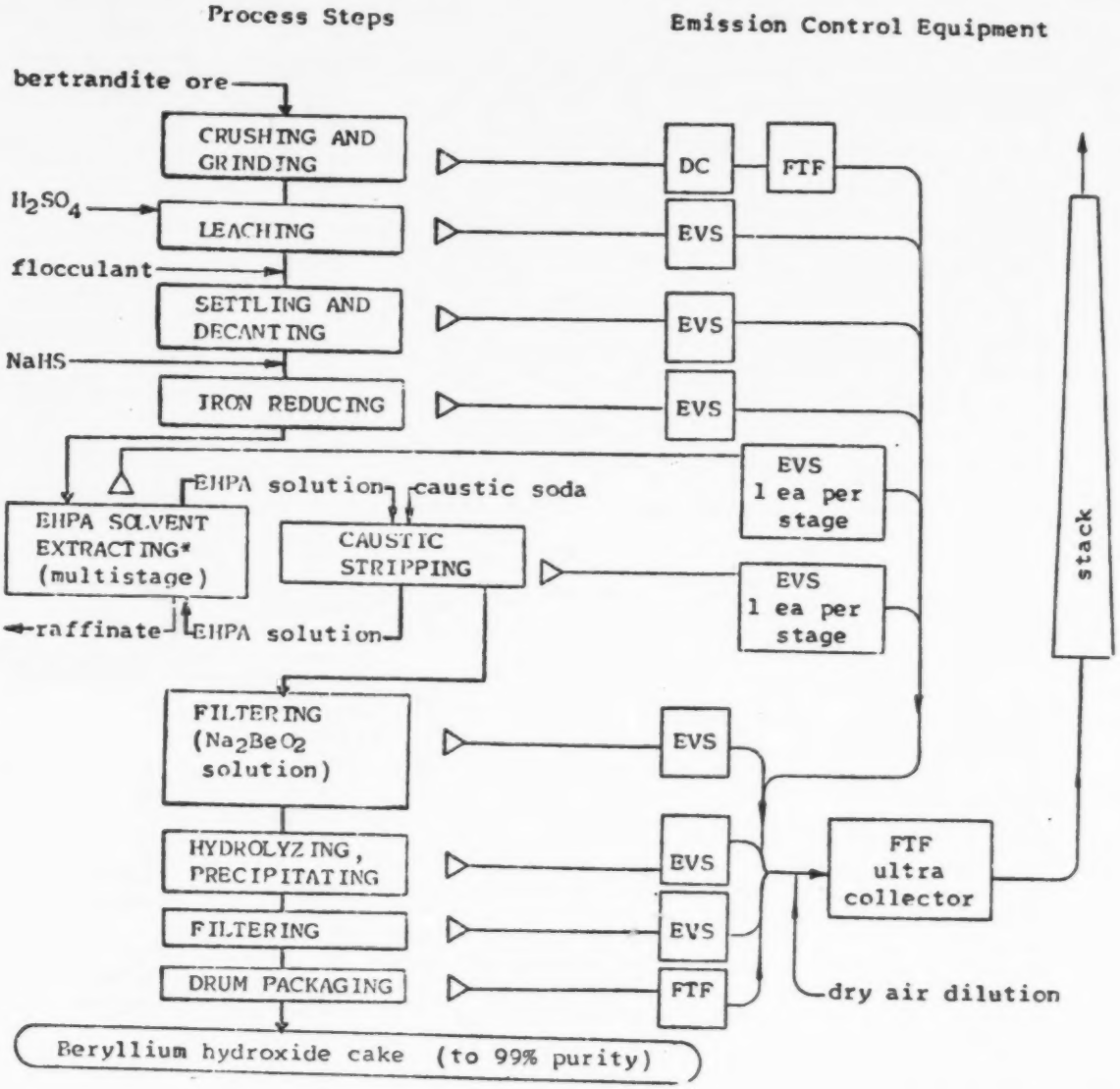
**** This fabric tube filter is termed an "ultra collector." It is in series with the first four items in the table and serves many additional sources throughout the plant. It is a shaker-type, compartmented filter, having orlon bags precoated by asbestos floats. The ultra collector is a secondary cleaner of "dry" exhaust gases. It handles about 65,000 cfm distributed 1/3 from the fluoride process, 1/6 from the $Be(OH)_2$-to-billet process, 1/6 from a research facility, and 1/3 from a $Be(OH)_2$ purification process.

FTF = fabric tube filter
DC = dry cyclone
VS = venturi scrubber
HST = hydraulic scrubbing tower
DC:FTF = a utilized dry cyclone, fabric bag filter (manual shaker type), used also for pneumatic transfer of dust collection at about 60 in. w.g. draft loss.

#Costs apply to March 1971.

Source: Reference 1

HYPOTHETICAL PLANT PROCESS: ORGANOPHOSPHATE EXTRACTION METHOD FOR CONVERSION OF BERTRANDITE ORE TO BERYLLIUM HYDROXIDE



*EHPA solvent is 0.25N di-2-ethylhexyl phosphoric acid with 2 wt vol percent isodecyl alcohol in kerosene

DC - dry cyclone
EVS - ejector venturi scrubber
FTF - fabric tube filter

Source: Reference 1

Figure 3-3

TABLE 3-4. AIR CLEANER COSTS#: BERTRANDITE ORE TO $Be(OH)_2$

Class*	Type	Air Flow** Rate, cfm	Maintenance Cost/Yr	Power*** Cost/Yr	Installed Cost	Annual Operating Cost
DC-4 ea.	High Efficiency	600 ea.	$ 70	$ 200	$ 7,375	$ 270
FTF-2 ea.	Shaker	1,200 ea.	235	240	11,520	475
EVS-16ea.	High Energy	600 ea.	685	11,410	83,200	12,095
FTF	Shaker	3,000	285	255	11,520	540
FTF	Shaker	30,000	3,320	4,400	46,080	7,720
			$4,595	$16,505	$159,695	$21,100

* EVS is 8" size, operating at 100 psig water pressure and providing 4 in. w.g. pressure drop.

** Actual flow rates. Rated flow rates may be as much as 30% higher. Rated flow rates, where known, are used for installed cost estimate.

*** Makeup water is included in power cost.

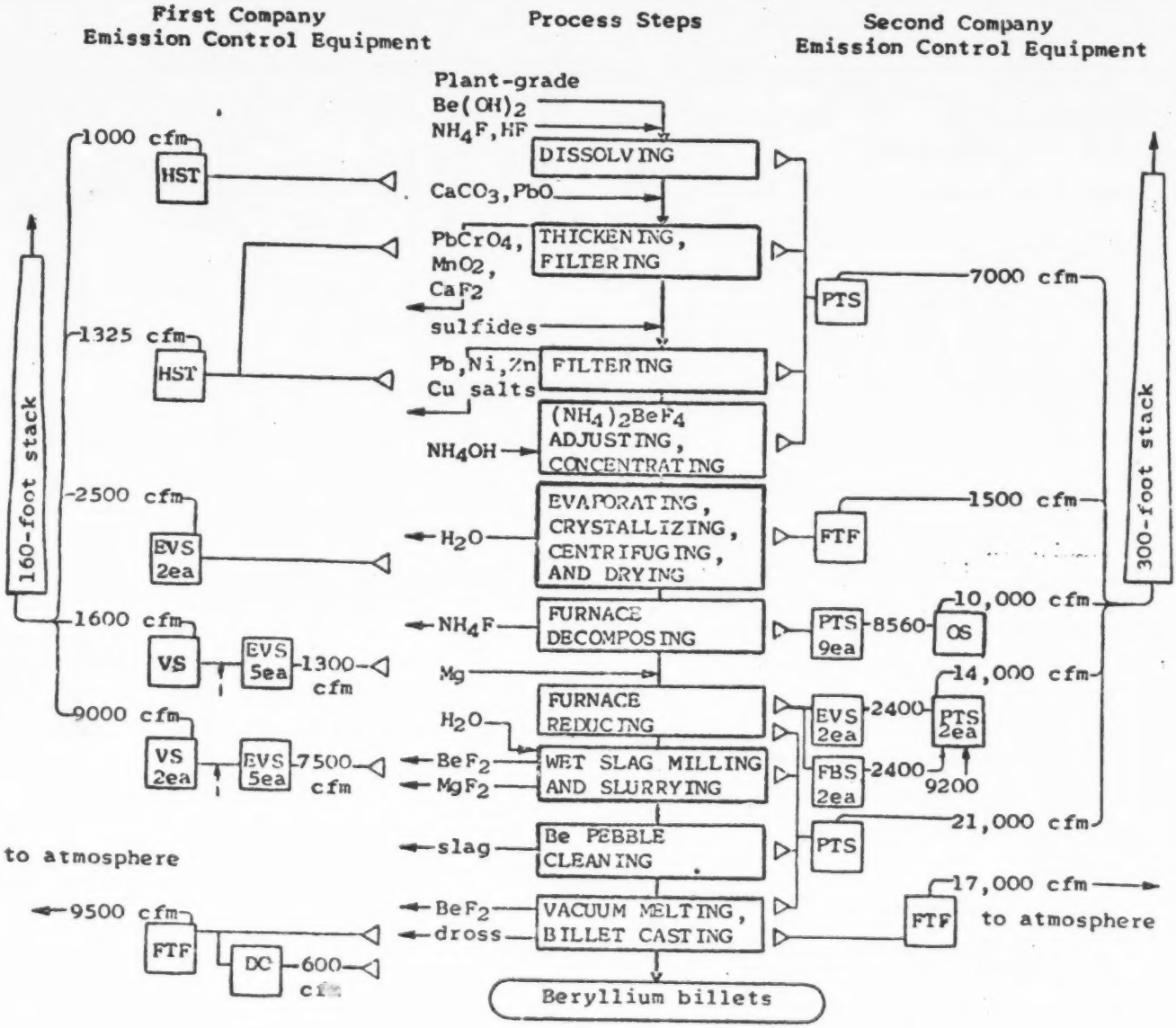
DC = dry cyclone
EVS = ejector-venturi scrubber
FTF = fabric tube filters, of which one (at 30,000 cfm) is an ultra collector, precoated with asbestos floats.

#Costs apply to March 1971.

Source: Reference 1

CONVERSION OF BERYLLIUM HYDROXIDE TO BERYLLIUM METAL BILLETS

(Showing alternative state-of-the-art emission control equipment)



PTS - packed tower scrubber
HST - hydraulic scrubbing tower
OS - orifice scrubber
FBS - floating bed scrubber
DC - dry cyclone
VS - venturi scrubber
EVS - ejector venturi
FTF - fabric tube filter

Source: Reference 1

Figure 3-4

TABLE 3-5. FIRST COMPANY AIR CLEANER COSTS[#]: $Be(OH)_2$ TO Be BILLETS

Class	Type*	Air ** Flow Rate	Maintenance Cost/Yr	Power *** Cost/Yr	Installed Cost	Annual Operating Cost
HST	Med. High Energy	1,000 cfm	$ 70	$ 230	$ 3,120	$ 300
HST	Med. High Energy	1,325	95	310	3,810	405
EVS-2 ea	High Energy	1,250 ea.	190	2,970	16,800	3,160
VS	High Energy	1,600	120	1,900	11,520	2,020
EVS-6ea	High Energy	270 ea.	120	1,930	18,000	2,050
VS-2ea	High Energy	4,500 ea.	640	10,630	34,560	11,270
EVS-5ea	High Energy	1,500 ea.	590	7,430	42,000	8,020
FTF	Bag Collapsing	9,500	900	790	20,750	1,690
DC	High Efficiency	600	25	55	1,850	80
			2,750	26,245	152,410	28,995
1/6 FTF ****	Shaker	1/6 x 65,000	1,015	1,240	13,450	2,100

* Among wet collectors, PTS and HST are here considered medium high energy types--PTS because of its 0.5-1.0 in. w.g. pressure drop per ft height, and HST because of pumping power requirements.

** Actual flow rates. Rated flow rates may be as much as 30% higher. Rated flow rates, where known, are used for installed cost estimate.

*** Makeup water is included in power cost.

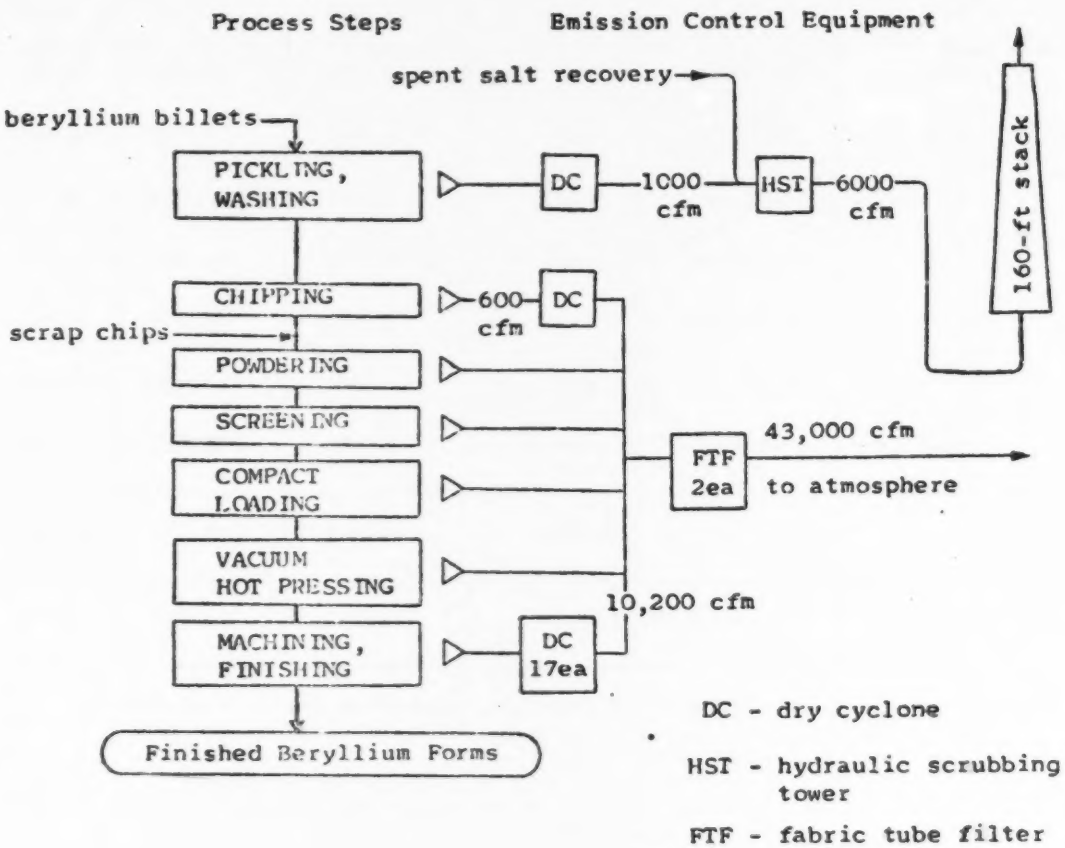
**** This fabric tube filter is termed an "ultra collector." It is a shaker-type compartmented filter, having orlon bags precoated by asbestos floats. The ultra collector is a secondary cleaner of "dry" exhaust gases. It handles about 65,000 cfm, distributed 1/3 from the fluoride process, 1/6 from the $Be(OH)_2$-to-billet-process, 1/6 from a research facility, and 1/3 from a $Be(OH)_2$ purification process.

HST = hydraulic scrubbing tower; EVS = ejector venturi scrubber
VS = venturi scrubber; FTF = fabric tube filter
DC = dry cyclone

[#]Costs apply to March 1971.

Source: Reference 1

CONVERSION OF BERYLLIUM BILLETS TO BERYLLIUM METAL FORMS



Source: Reference 1

Figure 3-5

TABLE 3-6. SECOND COMPANY AIR CLEANER COSTS[#]: $Be(OH)_2$ TO Be BILLETS

Class	Type*	Air** Flow Rate	Maintenance Cost/Yr	Power*** Cost/Yr	Installed Cost	Annual Operating Cost
PTS	Med. High Energy	7,000 cfm	$ 500	$ 2,750	$ 18,470	$ 3,250
FTF	Pulse Jet	1,500	140	200		340
PTS-9ea	Med. High Energy	160 ea	215	620	14,530	835
OS	Low Energy	10,000	710	1,580	8,650	2,290
EVS-2ea	High Energy	1,200 ea	180	2,860	16,800	3,040
PTS-2ea	Med. High Energy	7,000 ea	995	5,545	34,560	6,540
FBS-2ea	Med. High Energy	1,200 ea	165	475	8,300	640
PTS	Med. High Energy	21,000	1,495	8,315	27,700	9,810
FTF	Shaker	17,000	1,610	1,410	25,370	3,020
			6,010	23,755	154,380	29,765

* Among wet collectors, PTS and HST are here considered medium high energy types--PTS because of its 0.5-1.0 in. w.g. pressure drop per ft height, and HST because of pumping power requirements.

** Actual flow rates. Rated flow rates may be as much as 30% higher. Rated flow rates, where known, are used for installed cost estimate.

*** Makeup water is included in power cost.

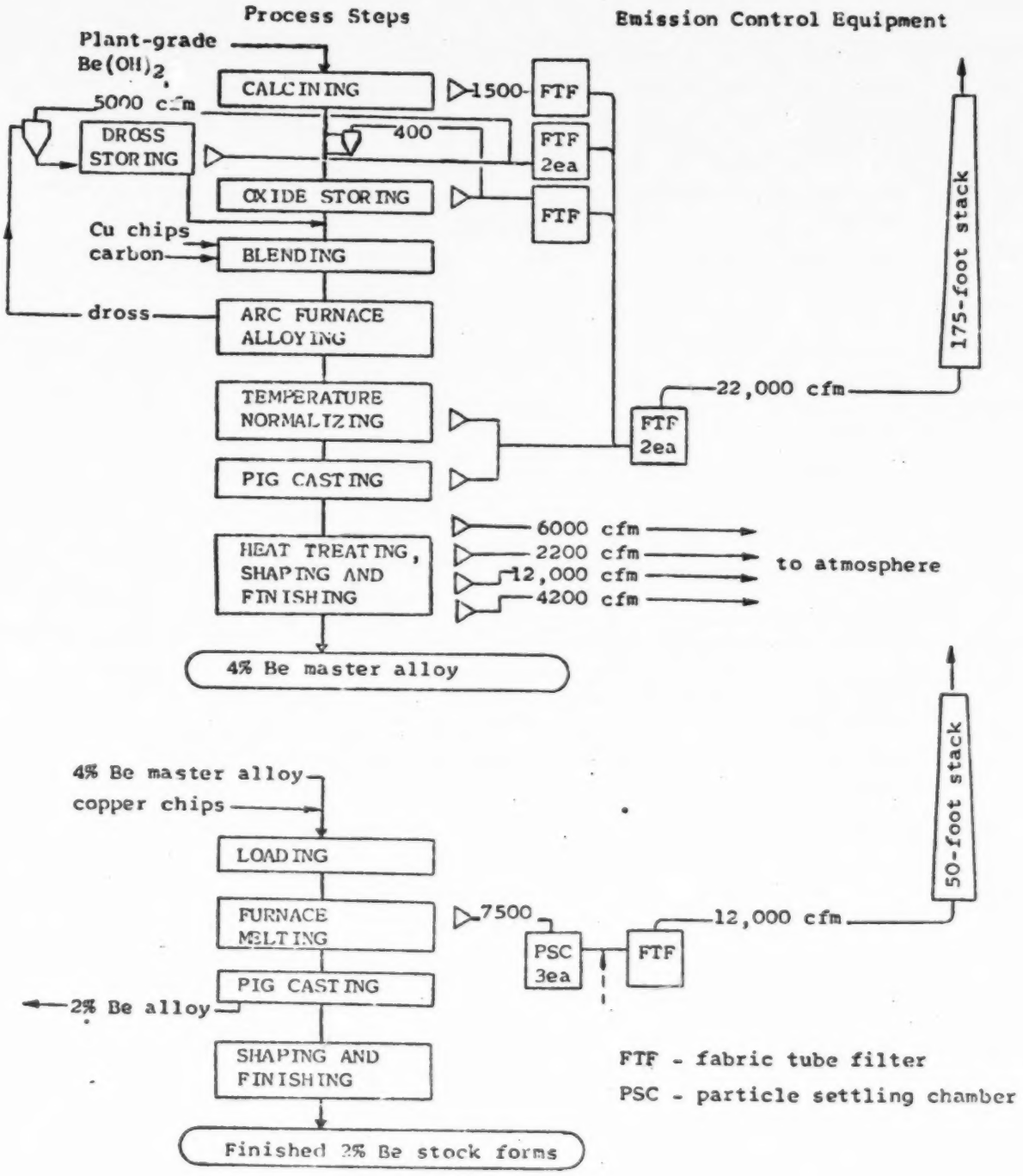
PTS = packed tower scrubber
FTF = fabric tube filter
OS = orifice scrubber
EVS = ejector-venturi scrubber
FBS = floating bed scrubber

[#] Costs apply to March 1971.

Source: Reference 1

CONVERSION OF PLANT-GRADE BERYLLIUM HYDROXIDE TO ALLOYS

(Showing state-of-the-art emission control equipment)



Source: Reference 1

Figure 3-6

TABLE 3-7. AIR CLEANER COSTS[#]: Be BILLETS TO Be METAL FORMS

Class	Type*	Air** Flow Rate	Maintenance Cost/Yr	Power*** Cost/Yr	Installed Cost	Annual Operating Cost
DC	High Efficiency	1,000 cfm	$ 35	$ 90	$ 2,300	$ 125
HST	Med. High Energy	6,000	215	1,715	23,040	1,930
DC-18ea	High Efficiency	600 ea	320	900	33,180	1,220
FTF-2ea	Reverse Jet	21,000 ea	4,070	6,270	50,700	10,340
			4,640	8,975	109,220	13,615

* Among wet collectors, PTS and HST are here considered medium high energy types--PTS because of its 0.5-1.0 in. w.g. pressure drop per ft height, and HST because of pumping power requirements.

** Actual flow rates. Rated flow rates may be as much as 30% higher. Rated flow rates, where known, are used for installed cost estimate.

*** Makeup water is included in power cost.

DC = dry cyclone
HST = hydraulic scrubbing tower
FTF = fabric tube filter

[#]Costs apply to March 1971.

Source: Reference 1

FTF - fabric tube filter

PTS - packed tower scrubber

M - mist collector

Figure 3-7

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CHAPTER 4

MERCURY

I. Introduction

Mercury is a silver-white metal, the only metal which is a liquid at most temperatures, normally encountered in the environment. Other properties which make it useful in various applications are its ability to amalgamate (dissolve) with nearly all other metals (iron being a useful exception), uniform volumetric expansion coefficient (as a liquid), high electrical conductivity, and (for some applications) toxicity.

Unfortunately, the toxicity of mercury and its compounds make it a hazardous substance to use, especially where its toxicity is not the reason for its use. Mercury is a relatively inert chemical. Its poisoning action is usually similar to that of other heavy metals (antimony, lead, etc.) in that it is a cumulative or chronic poison. Large doses of the metal or small doses of some of its more toxic compounds, however, can produce acute poisoning.

Persons seem to vary in their tolerance to mercury as a poison. One historical report claims that a person swallowed one pound (about two tablespoons) of mercury as a laxative; the treatment worked, after about three days, and there were minimal reported side effects. Other medical reports of persons swallowing, inhaling, or injecting metallic mercury "accidentally", in connection with work, or to commit suicide, indicate a wide range of toxic levels. Specific effects include skin sores, lung damage (when inhaled), kidney and brain damage, and psychological symptoms ("hatter's disease"). The wide variation in intake levels required to produce clinical mercury intoxication, particularly in chronic exposure cases, appears to be dependent upon the body's tolerance level and the slow but variable rate of excretion of the mercury rather than the specific exposure rate.

Elemental mercury has been identified by EPA as a hazardous atmospheric emission for several interrelated reasons. First, of course, is

its known toxicity. Second, mercury is highly volitile leading to industrial hygiene problems. The most widely-used method for maintaining low ambient air concentrations (50 g/m^3 TLV or less) inside plants is to ventilate work spaces with large amounts of air, thereby moving the mercury from inside to outside. There are frequently large process losses to the atmosphere in conjunction with the ventilation losses, or even where there are no ventilation losses. Industrial hygiene threshold limit values (TLV) are based upon working-day exposures; workers who live near sources of atmospheric mercury are therefore exposed in excess of the exposure assumed by the TLV. Third, it is believed by some researchers that, no matter how mercury is freed to the environment, it eventually ends up in the waters, where it can become concentrated in the aquatic food chain in particularly toxic forms (alkyl mercury compounds), endangering both higher animals and humans. Fourth, with the general population at risk, however small the risk, consideration must be given to the possible, and as yet unknown, synergistic effects of mercury and other environmental pollutants, particularly the other heavy metals. Finally, mercury is a widely-used industrial material.

The sources of mercury emissions to the atmosphere which have been analyzed for this project are: 1) primary mercury extraction plants; 2) secondary mercury recovery and refining plants; and 3) chlor-alkali production plants using mercury cells. These sources have been studied intensively by EPA, and proposed emission standards have been published. It should be noted that the estimated total atmospheric emissions of mercury from these sources in 1970 were about 50 tons, 60 pounds, and 70 tons, respectively. This is small compared with approximately 500 tons from coal combustion (assuming average mercury content of coal is 1 ppm) and about 150 tons from incineration and other waste disposal not associated with mercury processing. However, emissions per source are much more localized from the 18 largest mercury smelters and 32 mercury-cell chlor-alkali plants than the 400 fossil-fueled power plants and the thousands of incinerators and other waste disposal sites.

Additionally, technology for adequate control of direct mercury emissions to the atmosphere from the three types of sources studied is now commercially available or soon will be. It is therefore reasonable to begin economic analysis of cost impacts generated by control of these mercury emissions. The object of this portion of the final report is to present the basis used for estimating control costs to each of the three industries, the results of imposing those controls, and analyses of the expected economic impacts.

The remainder of this chapter discusses, for each of the three industries in turn, the operating techniques and parameters of the industry, the resulting uncontrolled emissions, applicable emission control techniques, emission standards, current control practices and levels of control (1970), costs of controls necessary to meet the standard, resulting emissions, and the various economic impacts of emission controls.

II. Primary Mercury Extraction

A. Occurrence and Recovery Techniques

Mercury is found in many minerals throughout the earth's crust including several that contain commercial quantities of other metals. The primary commercial source of metallic mercury throughout the world, however, is red cinnabar, which contains mercury as the sulfide. Ores used for commercial production in the U. S. typically average 4-5 lb of mercury per ton; a few extraction plants have occasionally produced from ore as low as two pounds per ton.

In the United States mercury is produced exclusively by pyrometallurgical processes, either by indirect or direct fired methods. Indirect firing (retorting) generally requires ores of 20 pounds or more of mercury per ton to be economically attractive. Little if any such ore is available on a regular basis in the U. S. Virtually all primary, or "prime virgin" mercury produced in the U. S. comes from ores that average 2-8 lbs of mercury per ton, produced by direct-fired processes.

The dominant direct-fired process used in the domestic primary mercury industry involves use of a rotating kiln inclined 5° to 15° above horizontal. Firing is done with the hot gases flowing up the kiln and ore flowing downward. Thirty to fifty percent excess air is admitted to ensure that the sulfur is oxidized, but still ensuring that temperatures remain well above the boiling point of mercury (357°C) until the gases reach the condenser. A pull-through hot fan is used to prevent escape of mercury vapor by providing a slight negative pressure to the kiln at all points. Spent or burnt ore leaves the kiln at about the sublimation point of cinnabar, 583.5°C. (1182.3°F). The burnt ore is removed to a dump pile after natural convective cooling.

After passing through the kiln, the hot gases, containing mercury vapor, entrained dust and soot, and corrosive gases such as sulfur oxides, pass through a cyclonic collector to remove most of the particulates. The captured dust may be treated for recovery of

adsorbed mercury by returning it to the kiln or to a separate retort. From the cyclonic collector the gases pass into the condenser for mercury recovery.

The condenser typically consists of two banks of vertical inverted U-tubes. Cast iron condensers predominate, although, a ceramic first stage is used in some plants. Mercury is condensed as the gas is cooled; cooling of the condenser is usually accomplished by ambient air, but (especially in hot weather) may be aided by spraying the condenser tubes with water. The condensed mercury collects at the bottom of the condenser tubes, where it settles into water in a container called a "launderer." The gases leave the condenser proper at 32°-49°C normally, saturated with mercury vapor. Generally, the gases then pass into a redwood settling chamber, which may contain baffles to assist in removing the entrained mercury droplets as the gases cool further by contact with the walls and by expansion. Direct water sprays are sometimes used to cool the gas. Gases then pass out a stack to the air.

At this stage, the mercury is usually contaminated with soot and other particles that escape the cyclone collector. It is, therefore, transported to a hoetable where it is mechanically mixed with lime to clean it. The cleaned mercury coalesces, collects at the low point of the table, and is bottled in iron flasks (76 lbs of mercury per flask) for shipment. This prime virgin mercury is pure enough for most uses.

Hydrometallurgical processing of mercury ores has been investigated and shows some promise, in that recovery cost for the two methods are comparable. The industry has shown little interest, however, primarily because of the technical complexity of the process as compared with roasting, and the high initial investment. If regulation of atmospheric emission of mercury from roasting imposes major control costs, the virtually emission-free hydrometallurgical process may become more attractive.

B. Emissions

Atmospheric emissions of mercury during the roasting process may occur at several points, including the burnt ore bin and bin

discharge, tailing dump, hoetable, and condenser exhaust. These emissions are essentially mercury vapor at concentrations below saturation vapor pressure except for the condenser exhaust, which is saturated with vapor and may contain entrained mercury droplets and mercury-containing particulates as well.

Emissions from the hot burnt ore can be virtually eliminated, and operating costs reduced, by using the hot rock to preheat the combustion air. Furthermore, yield of mercury might be increased slightly. Emissions from the tailing dump can be reduced by burying the tailings (returning it to worked-out portions of the mine); this would also reduce water pollution problems that typically occur in connection with tailing dumps. The hoetable can be controlled by enclosing it and using the requisite ventilation air as combustion air, again increasing yield slightly. Similar techniques may be used at other "passive" emission points.

The most significant source of mercury emissions by far, however, is the condenser exhaust. Hot gases coming directly from the kiln are generally not saturated with mercury vapor; however, since the method of recovery involves cooling the gas below the boiling point of mercury and its resultant condensation, the stack gases will be saturated with vapor, at least at the minimum temperature reached, and may also contain entrained droplets of mercury and mercury-containing ash and dust. The emissions calculated are based on losses of mercury as the saturated vapor only, and therefore are the <u>minimum</u> emissions expected.

Data made available to RTI by EPA indicate that, with 50% excess stoichiometric air, 470 m^3 of air are exhausted per ton of ore at the typical condenser exhaust temperature of 49°C (120°F). The saturation concentration of mercury at 49°C (120°F) is .118 g/m^3 (7.45×10^{-6} lb/ft^3). Stack emissions of mercury vapor per ton of ore processed are therefore approximately 56 g (.12 lb). The best control currently used at any mercury plant involves further cooling of the gases to 13°C (55°F) by use of direct water spray into the gas in settling chambers. With the combined reduction in gas volume

to 417 m^3/ton and the lowering of vapor pressure to .0073 g/m^3, the resulting mercury vapor emissions would be 3 g/ton. With the assumption that 2.25 kg (5 lbs) mercury per ton of ore is the average content of U. S. ore, and noting that U. S. prime virgin mercury production in the U. S. in 1970 was 27,281 (76 lb) flasks, approximately 410,000 tons of ore were smelted in 1970. Nationwide 1,240 to 23,100 kg (2,750 to 51,200 lb) of mercury would then be emitted by smelters from exhaust stacks alone. The actual figure is quite likely closer to the larger value, since (1) emissions rise rapidly with increasing temperature, and (2) no estimate of entrained droplets and mercury containing particulates has been included.

Independent estimates based on other data supplied to RTI by EPA indicate that 2 to 3 percent of the mercury originally in the ore is lost in stack gases, or 18,000 to 24,000 kg (40,000 to 60,000 lb) in 1970.

C. Emission Standard

The mercury emission standard selected for this study of primary mercury recovery is .95 g/ton (.0021 lb) per ore roasting (0.0021 lb/ton) facility and in no case more than 1156 g/day (2.56 lb/day).

The standard proposed subsequent to the completion of this study allows 2,300 grams (5.0 pounds) per 24 hour period. This should reduce control costs very significantly from the control costs estimated in this study.

D. Emission Control Techniques and Resulting Control

Control techniques which may be applied to the exhaust gas stream include: (1) further cooling followed by demisting; (2) alternative (1) followed by treated activated charcoal (TAC) adsorption; (3) conversion to hydrometallurgical recovery; (4) chemical scrubbing using sulfuric acid.

Alternative (1) involves an extension of current recovery techniques used by the industry, and is therefore least likely to cause technical difficulties or industry objections.

Alternative (2), if required for additional control,

likewise presents few technical problems,but has apparently not been tried with SO_2-contaminated gases.

Alternative (3) is a known technology involving floatation separation and electrolytic reduction; it is technically much more complex and has been shunned thus far by the U. S. industry. It should, however, drastically reduce emissions.

Alternative (4) has been reported in use at only one plant, in Finland. The process involves passing the cooled gas through a demister-type tower with a countercurrent flow of 90 percent sulfuric acid over the demister elements; this is followed by scrubbing of the gas with a 30 percent sulfuric acid solution. Passing the gas through the demister causes the mercury (and selenium) present in the gas to be converted to insoluble sulfides; the scrubbing process removes entrained acid mist and sulfur oxides. The mercury- and selenium-bearing acid is treated in a thickener, with clarified and strengthened acid returning to the process. The mercury selenium sludge is retorted to recover mercury and the residue is sent to a selenium recovery plant.

Cost have been developed for alternatives (1), (2), and (4). Alternative (1) will not meet the emission standard of .0021 pounds per ton of ore with a maximum of 2.56 pounds per day. Alternative (2) is capable of meeting the standard with a comfortable margin, with as little as .0004 pounds of mercury emitted per ton of ore, and allows a plant of up to 7,000 tons of ore per day to operate within the 2.56 pounds per day maximum. (A 7,000 tons per day plant would produce about 166,000 flasks per year.) Alternative (3) involves replacement of an entire plant's equipment. While the investment costs are comparable to those of new pyrometallurgical plant equipment, required operator retraining and technical complexity make this alternative extremely unattractive to the industry. The same comments apply to alternative (4), plus the comment that its economics appear to depend upon selenium recovery, which requires additional capital expense and which may not be feasible if U. S. mercury ores do not contain selenium or some other recoverable metal.

E. Costs of Control

Assuming selection of alternative (2) as described above, the costs shown in Table 4-1 are estimated to apply to a "large" plant (average of the 13 largest producers in 1970) of 72 tons ore/day processed, giving production of 4.75 flasks/day or 1,710 flasks/yr.

It is reasonable to assume that the mercury collected in the water-spray-demist operation is readily recoverable at almost 100% efficiency with essentially no additional cost. At the 1970 average price of $404 per flask, the additional 40 flasks recovered for sale are worth approximately $16,000. Thus, this portion of the control is more than able to pay its own way.

TABLE 4-1. CONTROL COSTS FOR MERCURY EXTRACTION MODEL PLANT

Control Step	Investment Costs ($1,000)	Annual Operating & Maintenance Charge ($1,000)
Cooling and Demisting 1/	$35.0	$10.0
TAC Adsorption 2/	9.9	15.5
Totals	$44.9	$25.5

1/ Cooling and Demisting: The gases are cooled to 4°C (40°F) by a direct spray of chilled well water, followed by demisting to removed condensed mercury droplets and mercury-laden water spray. Operating and maintenance costs based on $6 per flask produced.

2/ TAC Adsorber: Annualized costs are based on one carbon change per year, with no recovery value for the carbon.

F. Economic Impact

1. Industry Structure

Seventy-nine mines reported mercury production in 1970 compared to 109 in 1969. This is a reduction of about 28 percent. Domestic production was 27,303 flasks having a value of $11.1 million. This is an average of about 346 flasks per mine having an approximate value of $141,000.

Twelve mines produced 1,000 flasks or more, 5 produced between 500 and 999 flasks, and 10 produced 100 to 499 flasks,with 52 producing the remainder. California was the major producing state, contributing 68 percent of domestic mercury production, followed by Nevada, Idaho, and Oregon. Table 4-2 shows the location of U.S. mercury reserves.

Many of the mines that became inactive were small producers who found it uneconomical to continue production at the prices that prevailed during 1970. Production decreased only about 8 percent indicating a trend to fewer but larger producers. Some exploration and development work continued during 1970, however. Ore quality declined slightly with recovery averaging about 4.8 pounds per ton treated.

The mercury mining industry is operating well below the levels possible at higher prices. Since mid-1970 demand has declined leading to lowered prices and lowered output. While 1970 production was only 8 percent below 1969 production, 1971 production is expected to be about 33 percent below 1969 production. The dependence of production upon price is illustrated by Table 4-2 which estimates the U.S. mercury potential at various price levels (based on 1961 prices, costs, and technology).

Recovery of mercury as a by-product from the smelting of other ores is becoming significant although it has not been in the past. In 1969 280 flasks of mercury were recovered from zinc ore (mostly of New York origin) by a Pennsylvania smelter. In 1970 similar mercury by-product recovery from copper and silver ore was started in Ireland. There an annual recovery of about 1500 flasks is expected, although the mercury content of the ore is reported to be so low that it has not been assayed.

Table 4-2. THE MERCURY POTENTIAL OF THE UNITED STATES AT SELECTED PRICE LEVELS 1/

State	Mercury price per flask (76 pound flasks)					
	$100	$200	$300	$500	$1,000	$1,500
Alaska	-	14,500	33,500	69,500	124,500	142,500
Arizona	-	-	2,500	8,000	12,000	13,500
Arkansas	-	-	-	4,500	6,500	7,500
California	39,000	112,500	258,000	566,500	853,000	941,000
Idaho	-	-	20,500	37,500	65,000	72,000
Nevada	7,000	13,000	34,500	71,500	115,500	157,500
Oregon	-	-	12,500	34,500	55,000	71,000
Texas	-	-	17,500	35,000	54,000	59,000
Utah	-	-	-	-	500	500
Washington	-	-	-	500	1,000	1,000
Total 2/	46,000	140,000	379,000	827,000	1,287,000	1,465,500

1/ Based on 1961 costs and technology.

2/ Totals are cumulative.

Source: Reference 5

2. Market Structure

Mercury, sold in 76-pound flasks, is traded on a New York commodity market. However, about 90 percent of sales is private sales between producer and user with the price established from that reported by the commodity market. U. S. production usually makes up about 40 percent of U. S. consumption with imports accounting for the remainder of domestic consumption. A duty of $12.92 per flask was imposed on imports until January 1, 1971 when the rate was reduced to $11.40 per flask, in accordance with provisions of the General Agreement on Tariffs and Trade. This amounts to approximately five percent of market value.

Table 4-3 indicates the major uses for mercury. In this table any mercury required for initial inventory and start-up or expansion of electrolytic preparation of chlorine and caustic soda is included in "other". Consequently, Table 4-3 substantially understates the importance of chlorine and caustic soda. This has been the largest single end use for mercury when purchases for both current consumption and initial inventories are considered. Use in electrical apparatus is second in importance. Almost all of this is used for mercury batteries, by one manufacturer. The third largest use is for mildew proofing and antifouling paint. These three end-uses comprise over two-thirds of total 1970 domestic consumption. Because of its importance and the pollution problems involved, electrolytic production of chlorine and caustic soda will be discussed separately in a later section.

The mercury market is not at all concentrated on the buyer's side. There are a number of companies using mercury in or for production of a number of widely varying products. The largest purchaser consumed less than 5 percent of world production. For most users, the cost of mercury is a very minor part of total production cost.

In mid-1970, the Federal Government charged eight chlor-alkali producing companies with dumping significant amounts of mercury into waterways. Other significant users of mercury, such as

Table 4-3. MERCURY CONSUMED IN THE UNITED STATES, 1970

Use	Consumption (76-pound Flask)	Percent
Agriculture[1/2/]	1,811	3.0
Amalgamation	219	0.4
Catalysts	2,238	3.6
Dental Preparations	2,286	3.7
Electrical Apparatus	15,952	25.9
Electrolytic Preparation of Chlorine and Caustic Soda	15,011	24.4
General Laboratory Use	1,806	2.9
Industrial and Control Instruments	4,832	7.9
Paint:[2/]		
Antifouling	198	0.3
Mildew Proofing	10,149	16.5
Paper and Pulp Manufacture[2/]	226	0.4
Pharmaceuticals	690	1.1
Other[3/]	5,858	9.5
Total Known Uses	61,276	
Total Uses Unknown	227	0.4
Grand Total[/]	61,503	100.0

1/ Includes fungicides and bactericides for industrial purposes.

2/ 1971 and 1972 decisions by EPA will essentially eliminate these markets.

3/ Includes mercury used for installation and expansion of chlorine and caustic soda plants.

agriculture and the paper industry, have since been charged with contributing to pollution of the environment. Subsequently, the total use of mercury has dropped about one-third. No new chlor-alkali plants using mercury cells have been completed since early 1970 and at least three have closed or announced plans to close. Through improved plant operating procedures those remaining have reduced mercury consumed as processing losses by about 27 percent. Consumption of mercury per ton of chlorine produced was 0.43 pounds in 1970, compared with a level between 0.5 and 0.6 pounds prevailing during the previous 8 years.

In addition, several industries have curtailed or eliminated the use of mercury in their processes. The paper industry has accelerated its trend away from mercury and no longer uses mercury compounds for in-process slime control. Methyl mercury compounds are no longer licensed by the U. S. Department of Agriculture to be used in treating seeds for agriculture. One major mining company has discontinued use of the mercury amalgamation process for gold recovery.

The mercury industry operates in a world market where the U. S. consumes about 22 percent of world production, with 60 percent from imports. Major world producers, in order of importance, are the Soviet Union, Spain, Italy, Mexico, United States, and Canada. Canada became a major mercury producer in 1968 with the opening of a highly mechanized mine producing ore similar in quality to U. S. ore. In 1970 Canada contributed about 9 percent of world production. Three-quarters of this was exported to the U. S., replacing Spain in 1970 as the major mercury exporter to the U. S. Spain is second and Italy is third in supplying mercury to the U. S. Both of these countries have been producing mercury from extremely high grade ore (compared to that of the rest of the world) for several hundred years. Mexico is another source of U. S. imports and a major contributor to world production. However, the importance of Mexican production is difficult to estimate because production statistics from Mexico

are undependable. Trade sources estimate as much as half of Mexican production moves through illegal channels and is unreported to avoid Mexican income, production, and export taxes.

3. Prices and Trends

Total U. S. consumption of mercury in 1970 dropped 22 percent from 77,988 flasks in 1969 to 61,503 flasks, and consumption in 1971 is running at an annual rate of about 55,000 flasks. As consumption has fallen, so have prices. Average price per flask was $505.04 in 1969, $407.77 in 1970, and closed at $225 at the end of trading in 1971 although prices had averaged $285 or higher for the first three quarters of the year (Table 4-4). Since 1965 the overall price trend has been down, especially since the mercury pollution publicity of mid-1970.

Factors believed to have contributed to price decline are increased world production, U. S. Senate hearings on the effects of mercury on man and the environment, cancellation of registration of 48 mercury biocides, and reduced consumption resulting from the general economic recession.

4. Impact of Control Costs on the Industry

For domestic firms, break-even production cost averages between $300 and $400 per flask, varying with the quality of ore being worked and the difficulties encountered. Ore bodies that can be worked with open pit methods are less expensive to operate. Deeper mines that require underground mining methods may encounter water and ventilation problems. For most mines exploration and development costs are in addition to the break-even production costs reported. Operations can continue in areas explored and developed until they are exhausted. Firms must then either make additional investments in development and eventually exploration or close.

Current prices are so far below costs that domestic producers have abandoned operation until only a few of the largest remain.

Table 4-4. AVERAGE NEW YORK PRICE OF MERCURY

Year		Price ($/Flask)
1960		$ 210.76
1961		197.71
1962		191.21
1963		189.45
1964		314.79
1965		570.75
1966		441.72
1967		489.36
1968		535.56
1969		505.04
1970		407.77
1971	1st Quarter	341.34
	2nd Quarter	285.89
	3rd Quarter	288.30
	4th Quarter	253.46
	Year	295.00

Source: References 3 and 4

One is operating on ore already broken out (and therefore ore with a very low marginal cost) and plans to close when that is exhausted. Another producer has reduced output to one-quarter, having already closed two mines. This company reported a loss last year and does not expect to remain open much longer. A third company continues to operate at a loss hoping prices will increase since water incursion may make it unlikely that the mine can ever be re-opened if it is shut down.

Future prospects for the U. S. industry are dim. Competition from Spanish, Italian, and Canadian producers that have either higher quality ore or highly mechanized operations is intense. Some foreign producers operating very high grade ore have curtailed operations and withheld production from the market because of low prices. GSA stockpiles declared surplus are large. Industry stocks are currently low, but the mercury released for market each time a mercury cell chlor-alkali plant closes is large. A revival of the domestic mercury industry within five years is doubtful.

Any costs associated with required air pollution control equipment will serve to hasten the demise of the few firms continuing to operate. For those that have closed, air pollution control costs will raise costs should they try to open again and thereby help prevent such attempts. Further, the larger firms will be favored because they come the closest to having, or being able to raise, the necessary financial resources. Air pollution control costs will also favor certain process changes. Currently, mercury is extracted from unconcentrated ore close by each mine. A requirement for more elaborate extraction plants will favor floatation concentration of ore and shipment of the concentrate to a central extraction plant owned cooperatively or by a large firm.

5. Price Impact

Any analysis of the economic impact of air pollution controls imposed on an industry that is shutting down because prices no longer cover operating costs is largely academic. Producers absorb the costs from nonexistent profits nor can they pass the cost on in the form of price increases. Some firms may continue operating without controls until enforcement causes them to close.

III. Secondary Mercury Recovery

A. Mercury Recovered and Methods of Recovery

Mercury is recovered from many products and pieces of equipment in which it has been used, when their useful life is over. In addition, it is often highly purified for special uses, as in scientific instruments. These operations are all undertaken by the industry known as secondary mercury recovery.

The major amount of mercury recovered currently is received in liquid form, containing primarily dissolved metallic impurities. Prime virgin (primary) mercury is occasionally purified by the same techniques as "used" mercury. Solids from which mercury is recovered include dental amalgams, chemical sludges, scrap dry cells and batteries, and junked equipment in which mercury was used, such as mercury stills and mercury switches. For accounting purposes, releases of mercury from government stockpiles are reported in the literature as part of secondary mercury production.

Recovery of mercury from contaminated liquid is really a purification process from which the contaminants are occasionally recovered as by-products. The three techniques by which the purification is accomplished are: (1) distillation; (2) solution purification; and (3) oxygenation ("oxification" in the trade). Mercury is recovered from solids by methods similar to those used in primary recovery, generally indirect-fired retorting. These four processes, each of which can lead to significant emissions, are described separately below, along with the bottling process where the recovered mercury is packaged for shipping.

Other emissions can occur in the secondary recovery plant from miscellaneous handling processes, such as filling of apparatus. This may be especially true if hot operating equipment, such as a stillpot or retort, is not adequately cooled before cleaning and refilling. Also, emissions are expected from accidental spills, if these are not properly cleaned up or covered.

1. Distillation

Dirty mercury is distilled by heat under a vacuum of approximately .01 torr, the vacuum being drawn on the condenser side of the still. Cooling of the distilled vapors is typically done in a water-jacketed condenser. Where very-high purity mercury is required, a double or even triple distillation of the mercury may be performed. In installations where multiple distillation is done frequently or routinely, the equipment may be an enclosed series of stills which require no external transfer of liquid from one distillation step to the next. Alternatively, the mercury may undergo a mixture of the various purification processes, depending upon the particular contaminants.

Major emissions of mercury from the distillation process itself come from the vacuum pump exhaust, which is generally vented to the plant's workroom air. The advantages of distillation under a vacuum presumably are (1) a lowered boiling temperature of mercury resulting in lower heating requirements and/or more rapid distillation, and (2) removal by the vacuum system of dissolved vapors and gases. Typical ventilation flow rates for a 3000 flask/year plant are 2000 to 4000 CPM. Emissions from the workroom are then expected to be 2.85-5.5 mg/min at the new TLV or 5.7-11 mg/min at the current TLV. At the maximum exhaust rate and the current TLV this results in emissions of .0348 lb/24-hr day or 12.5 lb/yr if the plant operates continuously. Emissions from the distillation process itself must be much below this, for the total emissions to inplant air also include those from uncollected spills, transfers, bottling, etc. The total estimated loss amounts to a maximum of .0035% of the total plant throughput of 3000 flasks and may be considered a negligible loss, at least economically.

The prime difficulty with the above calculation is the assumption that the industrial TLV is being observed. There are no data to indicate that it is <u>not</u> being met, but neither are there data verifying that it <u>is</u>. However, the overall loss rates estimated above seem small, in view of the potentials

for emission which exist from leaks, spillages, and other accidents. If spills are not properly cleaned up or covered, evaporation from the large surface areas exposed will lead to emission problems.

Nonetheless, it appears that losses from the production process itself will be very small, as indicated above. It is anticipated that no control for vapor losses from production processes would be required unless new data giving a radically altered picture are obtained. However, if controls are required, the following techniques would seem applicable:

(1) enclosed working compartments for the transfer of both dirty and clean mercury and removal of stillpot residues (which are up to 95% mercury). This will reduce spills and evaporative transfer discharges to an absolute minimum;

(2) control of the vacuum pump discharge with an activated carbon adsorption filter.

Installation of these controls would reduce overall plant emissions to a truly negligible level after the work area is adequately cleaned of existing residues from spills. It is anticipated that ventilation requirements would be reduced to those required for normal worker comfort unless a major accident occurred. Costs of control systems are estimated to be very low. Activated carbon can adsorb 10% its own weight of mercury before becoming spent. Supposing that half the total emissions of 12.5 lb per year come from the vacuum pump exhaust, or 6.25 lb, a total of 62.5 lb of charcoal/yr would be required if all the mercury is adsorbed. In this small quantity, the required treated, activated carbon may cost as much as $125 per year. Assuming small "cartridges" of carbon requiring 6 changes per year, one hour's total labor for between $5 and $10 is reasonable. Installed cost, mostly labor, would be $50-$100 and necessitate no downtime. Annualized costs would then be less than $150 per vacuum pump.

2. Solution Purification

Solution purification involves removal of (primarily metallic) impurities by dissolving the impurities in dilute nitric acid.

The processing takes place in a stainless steel leach tank. The dirty mercury is emptied into the tank, covered with a layer of dilute acid, and air is bubbled (sparged) through the mercury and acid to promote mercury-acid contact. The gas flow rate is generally 1-5 cfm. After a sparging time of several hours the cleaned mercury is separated from the contaminated acid by decantation; the mercury is then water-washed to remove all traces of acid, and then bottled.

Although there are several points within the process stream which may emit mercury to the air, only the sparging air stream carries mercury directly into the outside air. The other sources result in emissions to the workroom, which must be kept at or below the industrial TLV. Maximum emissions carried by the sparging air may be calculated assuming that (1) the air becomes saturated with mercury during the bubbling process, and (2) no mercury droplets are entrained in the exhaust air. With these assumptions, and assuming an air temperature of 86°F(containing 1.8×10^{-6} lb mercury vapor/ft^3) and flow rate of 5 cfm, the maximum mercury emissions would be .013 lb per 24 hr day. Lower air temperatures, partial "scrubbing" of the air by the nitric acid layer and/or lower sparging rates would all lead to lower atmospheric emission rates.

Losses from the other emission points lead to contamination of the workroom air, which is exchanged with atmospheric air to produce the required new TLV of 50 $\mu g/m^3$. Ventilation flow rates of 2000 ft^3/min are reported as typical of solution purification plants. The losses from ventilation then would be 0.01 lb/24-hr day, leading to a maximum plant-wide loss rate of 0.023 lb per day.

Emission can occur by evaporation from the spent leaching acid and waste wash water. These are not considered in this

analysis since either the acid will be stored, covered for reuse or discarded with the waste water.

Emissions from the sparging process can be reduced by passing the sparging air through a treated activated carbon adsorber. In order to prevent difficulties with the adsorber which may be caused by nitric acid vapors, it may be necessary to water wash ("bubble") the sparging air before adsorption. If the air is cooled during washing, this might result in a reduction in the mercury content as well, but it would not be a significant reduction. Costs of control would be low, even as a percentage of current plant investment; uncontrolled emissions are so small, however, that even this expense is probably not necessary.

[Emissions from the process of bottling the cleaned mercury are discussed elsewhere.]

3. Oxygenation

The oxygenation cleaning process is accomplished in a manner similar to that of the solution purification process. The differences are: (1) oxygenation depends upon oxidation of impurities to filterable solids, so that no acid leachant is used; (2) there is no washing process, but the cleaned mercury is filtered; (3) the sparging rate is much lower than that of solution purification, typically 0.2 cfm.

The sparging air from the oxygenation process is typically scrubbed with water and cleaned with activated charcoal before venting. As a result emissions would be negligible, down from the maximum possible at 86°F of .00052 lb/day. Emissions from other sources would be similar to those from solution purification, which were calculated as 0.01 lb/day.

Control of the emissions from the oxygenation process itself would not seem to be necessary, in view of their low quantity. However, the current use of water scrubbing on the sparging gases indicates that there may be a problem with entrained mercury droplets, which would be recoverable using the water scrubbing technique. There are no further data on this point, however.

Additional mercury emissions associated with oxygenation, but not directly connected with the process, arise from recovery of mercury from the filter cake (usually by retorting), and bottling. Both of these processes are discussed in later sections.

4. Retorting

The technique of retorting for mercury recovery is used when the mercury is contained in a solid or semisolid material, such as dental amalgams, mercury electrical cells, and stillpot residues.

The retorting operation is similar to both distillation and primary smelting. If the scrap contains a high percentage of mercury, the material is generally treated in an externally heated pot; no process air is required, since the mercury does not have to be chemically liberated, and the non-mercury residual may also be a valuable by-product. Where low concentrations of mercury are involved, the mercury-bearing material is placed in an oven-type cabinet on trays. In either process, as the material is heated, the mercury volatilizes and passes into a water-cooled condenser. In some cases, the gases may be further treated by additional chilled water cooling and/or water sprays. The residual gases and vapor are then exhausted to the atmosphere.

Data on exit gas concentrations of mercury, recovery rates, etc., are not available. It is expected, on the basis of process type, that recovery rates of mercury from the hot vapor would be comparable to those of the primary smelting industry, particularly from closed, externally-heated vessels. Emissions from oven-type retorts, which use direct-contact heating, are much harder to estimate because of the highly variable mercury content and heat capacities of the charged materials, which will result in highly variable vapor concentrations in the gas stream. Also, contamination of the gases by other volatile materials, or by fine particulate which may carry

mercury away, is impossible to specify. Gas flow rates per unit of mercury charged or produced are not calculable, but are expected to be lower than for comparable primary smelting production.

Need for controls, therefore, is almost impossible to specify, since production rates, ratios of closed to oven type systems, etc., are not known. Applicable control systems beyond those already in use might be refrigerated cooling and demisting of the gas stream or use of treated activated carbon or other adsorbant. However, there is no indication of their applicability in the literature. Calculations of control costs, therefore, have not been made.

B. Bottling

The mercury produced by the various recovery and purification processes is stored in reservoirs until enough has been accumulated to be bottled, usually in the standard 76-lb iron flask. Emissions of mercury vapor to the atmosphere can occur from the exposure of the mercury to the atmosphere plus splashing during the filling process.

About 96% of the secondary mercury processed in the U.S. is bottled by a metering apparatus which is open to the workroom atmosphere. In some installations the bottling apparatus is in the same room as other secondary processing equipment, while in other plants it occupies a separate room. Losses from natural evaporation, etc., are too small to measure directly. With a maximum room ventilation rate found of 4000 cfm at the required TLV of 50 $\mu g/m^3$, however, the losses would be a maximum of 0.02 lb/day.

The remaining 4% of U.S. production of secondary mercury is bottled using the same apparatus, but enclosed in a box of about 0.5 m^3 volume. The box contains a door, a window, and glove ports. Operation of the box involves opening the door to remove full flasks

and insert empty ones, sealing the door, and filling the flasks. Emissions from the box, assuming that the air inside is saturated with mercury at warm room temperature (77°F) and that the air is completely exchanged when the door is opened, are .00002 lb per flask transfer cycle. Enough flasks can be contained in a box of 0.5 m^3 size that 2 transfer cycles/day would be adequate for most plants. Emissions would then be $4x10^{-5}$ lb/day.

Emission controls on bottling would not seem to be necessary in most cases, unless the bottling operated continuously for a long period of time. If the closed box filling arrangement is used, that would certainly be adequate control. The cost of this box is estimated at roughly $300-$500. There would be some economic advantages to using the box, since it allows better control and recovery of spills, reduced labor cost for control of spills, and would allow a somewhat more relaxed employee attitude because of reduced emissions concern. Whether these factors would allow recovery of the cost of the box over its useful life may depend upon the situation in which it is used, but it very well could. In any case, it would seem to be a minor expense.

C. Costs of Control

Control costs for the secondary mercury industry are minimal. Some plants already have, as good operating practice, some of the suggested equipment. Others do not have it and do not need any additional equipment to meet control standards. Table 4-5 shows the estimated control costs for the industry based on the assumption that every firm in the industry must install control equipment. Actual expenditures would be much less.

Table 4-5. Estimated Emission Control Costs for the Secondary Mercury Industry, 1970

	Investment Cost	Annual Operation & Maintenance Charge	Annualized Costs
Activated Carbon Absorption Filter	$ 2,400	$ 4,800	$ 5,280
Bottling Box	12,800	800	3,360
Totals	$ 15,200	$ 5,600	$ 8,640

D. Economic Impact

1. Industry Structure

There were 32 active firms reported in 1970, each with a single plant. Firms, as would be expected, are located close to sources of junk mercury or mercury containing scrap. They are located primarily in the New York-New Jersey, Chicago, Los Angeles, and San Francisco Bay industrial areas.

Much of the mercury processing by the industry is on a consignment or fee-for-service basis. The mercury or mercury containing scrap is sent to the mercury processor to be cleaned, and the processed mercury is then returned without a change in ownership. The processor charges for what he has done.

2. Market Structure

Mercury recovered by the secondary industry is (except for redistilled mercury) no different from that produced by the primary industry. The product of each industry is directly

substitutable for the product of the other industry, and therefore the product of the secondary industry is sold in the same markets and at the same prices as primary mercury.

Redistilled mercury is somewhat different in that the cost of the added processing must be covered by the price. However, redistilled mercury can be produced from mercury recovered by the secondary industry or manufactured by a primary producer. Therefore, the higher price for redistilled mercury in only enough to cover the added cost plus a reasonable profit on the service. There are enough firms in the industry to prevent the realization of monopoly profits. In addition, a firm requiring redistilled mercury can buy mercury on the open market and have it redistilled if the price differential for redistilled mercury appears to have become unreasonable.

Table 4-6 shows the 1970 consumption of primary, secondary, and redistilled mercury. Electrical apparatus is the principal use for both redistilled and secondary mercury. Other major uses for redistilled mercury in order of importance are for industrial and control instruments, dental preparations, and general laboratory use. These same industries are important to secondary mercury, but industrial and control instruments rank fourth instead of second.

E. Impact of Control Costs

Control costs for the secondary mercury industry, both as a whole and for individual firms, are so low that the impact will hardly be noticed. Based on 1970 secondary mercury production of 8,051 flasks, and assuming every firm requires control equipment, investment costs would at most amount to about $2.00 per flask. Annualized costs would be at most about $1.00 per flask of 1970 production (1970 price averages $407.77). Costs are so minimal that firms would have no difficulty making the necessary investment and recovering the increased costs from lower operating costs, by slightly higher charges for processing mercury for others, or by slightly lower

Table 4-6. MERCURY CONSUMED IN THE UNITED STATES IN 1970 (FLASKS)

	Primary	Redistilled	Secondary	Total
Agriculture [1/2/]	1,811	---	---	1,811
Amalgamation	206	3	10	219
Catalysts	1,916	225	97	2,238
Dental preparation	166	1,372	748	2,286
Electrical apparatus	11,432	3,469	1,051	15,952
Electrolytic preparation of chlorine and caustic soda	14,749	---	262	15,011
General laboratory use	689	495	622	1,806
Industrial and control instruments	2,124	2,353	355	4,832
Paint:[2/]				
Antifouling	193	5	---	198
Mildew proofing	10,149	---	---	10,149
Paper and pulp manufacture[2/]	223	---	3	226
Pharmaceuticals	280	362	48	690
Other	5,668	12	178	5,858
Total known uses	49,606	8,296	3,374	61,276
Total uses unknown	15	69	143	227
Grand total	49,621	8,365	3,517	61,503

1/ Includes fungicides and bactericides for industrial purposes.

2/ 1971 and 1972 decisions by EPA will essentially eliminate these markets.

Source: Reference 3

payments for mercury and mercury containing scrap. It appears that much of the cost for those firms that must install control equipment would be recovered from lower operating costs.

F. Impact on Prices

Air pollution control costs for the secondary mercury industry would have no impact on the price of mercury. These prices are determined competitively in a world market and the domestic secondary mercury industry is too small to have much impact. Then, too, the change in cost is small. At most, a slightly increased fee schedule for processing mercury for others and slightly lower payments for scrap mercury might result. Any such changes would be so small as to go virtually unnoticed.

IV. MERCURY-CELL CHLOR-ALKALI PRODUCTION

A. Introduction

Virtually all chlorine used in the U. S. is produced by one of the available electrolytic methods, primarily electrolysis of brines and of fused chlorides. By far the largest production is from brines of alkali-metal chlorides, with the production of chlorine gas at the anode and the alkali metal (sodium or potassium) at the cathode. In the diaphragm cell process the alkali metal reacts directly with the water to form the corresponding hydroxide in solution, and hydrogen gas. The diaphragm, characteristic of the process, serves to separate the brine and caustic solutions. In the mercury or amalgam cell process a layer of mercury over the normal carbon serves as the cathode, the mercury-brine interface acting analogously to the diaphragm. The alkali metal amalgamates with the mercury and the amalgam is tapped from the cell. The amalgam is then passed through a second cell known as a denuder, in which the alkali is stripped from the mercury by pure water, forming hydroxide and hydrogen gas. The cleaned mercury is then returned to the cell. The mercury cell process is the one which is considered in this report.

The chlorine produced by the two processes is essentially identical and interchangeable; but the caustic is not in some applications. Caustic from the diaphragm cell process is generally of relatively low concentration (15%), and contains chloride or hypochlorite ions, even if in low concentrations, making it unsuitable for use in synthetic fiber production. Mercury cell caustic, on the other hand, although free of chloride and hypochlorite contamination, and of 50%-73% concentration, contains mercury. It is therefore unsuitable for photographic chemical applications and some other uses.

B. Mercury Emissions

There are several points from which mercury can escape to the atmosphere in a mercury-cell chlor-alkali operation. The actual amount of mercury emission from each type of source may in fact vary

from plant to plant, since several types of cells are in use, and the condition of the cells may vary with age and plant maintenance policy. However, the emissions described below are believed to be representative. Total amounts of emissions, where given, refer to a plant producing 100 tons of chlorine per day unless otherwise noted.

Purified and nearly saturated brine solution and mercury returned from the denuder are fed concurrently from the inlet end box into the cell. The end box serves to keep a reserve of mercury and brine ready for smooth operation and to keep the mercury covered with brine. The spent brine and amalgam are collected in the outlet end box. The brine is tapped off from the end box and usually dechlorinated and is at least partially recycled.

The chlorine gas, which contains water vapor and perhaps some mercury vapor, is dried by scrubbing with concentrated sulfuric acid. Inert gases are removed. The spent sulfuric acid contains essentially all of the mercury from the chlorine gas, so that there is virtually no loss with the chlorine product. The chlorine gas is then compressed and occasionally liquified.

Ventilation air supplied to the outlet end box contains mercury and mercury compounds, when it leaves the end box, in amounts which depend largely upon the amount of ventilation air used. The amount of air used, in turn, depends upon cell design, plant age, and plant operating procedures. Current trends are to reduce end box ventilation flow as much as possible in new cell designs and by modifications to existing cells. Currently, it is believed that the maximum total outlet end box ventilation flow for a 100 ton/day chlorine plant is 1500 cfm. If the gas is saturated with mercury vapor at 60°F and contains no particulate mercury, this leads to a mercury loss from the plant of 1.2 lb per 24-hr day in the absence of any controls.

The alkali amalgam is bled from the outlet end box into the denuder or decomposer, where it is reacted with purified water in a short-circuited "cell" to produce the alkali caustic at a high purity and about fifty percent, by weight, concentration at the final outlet. The by-product hydrogen gas results from this reaction,

and is typically saturated with mercury at 210°F. The minimum treatment known to be applied to the hydrogen stream is cooling to about 110°F followed by demisting to remove the condensed mercury droplets. The approximate hydrogen flow rate at this temperature is 750 cfm from a 100 ton per day chlorine plant. At this flow rate, if the hydrogen stream is then flared or discharged, the mercury emissions are approximately 4.1 lb per 24-hour day.

The alkali caustic solution from the denuder is filtered to remove suspended mercury droplets and other impurities. The resulting filter cake is retorted in a manner very similar to that used in secondary mercury processing. The recovered mercury is returned to the cells for reuse. Mercury recovered from the spent chlorine-drying sulfuric acid may also be treated in this way. Emissions from the retorting operation are estimated to average .002 lb per 100 tons of chlorine gas produced.

Further processing of the caustic solution may be undertaken to make the concentration 73% by weight, or the material may be heated to produce anhydrous caustic alkali. No significant mercury emissions are indicated to result from this process.

Probably the largest amount of mercury emissions occurs from ventilation of the cell room. Mercury is "routinely" spilled in small amounts, lost as vapor in leaks, may by-pass pump seals in mercury handling systems, and escapes as vapor when cells are broken down for maintenance. In addition, significant losses may occur, on an infrequent basis, during catastrophic cell failure. Aside from cell failure, however, the direct losses of mercury vapor are probably small, although they will vary with cell design and equipment condition and age. Because of the high cost of mercury, these losses are kept at a reasonable minimum. Losses from spilled liquid, however, unless it is immobilized or cleaned up, can mount up at a rate depending upon the temperature of the cell room (usually quite warm because of power usage) and the exposed surface area of the mercury. Losses to the atmosphere measured from these sorts of

data are difficult to estimate. However, ventilation rates have been obtained for cell rooms ranging from 100,000 to 1,000,000 cfm for each 100 tons per day of chlorine produced. On the assumption that the required TLV of 50 $\mu g/m^3$ represents the actual airborne mercury, the range of mercury losses in the cell room air at these flow rates is 0.45 lb to 4.5 lb per day. Data currently available indicate that cell room mercury emissions probably increase with plant size, but not in direct proportion to plant capacity. Although for smaller plants it would appear that mercury emissions in cell room air could readily exceed those from all other sources combined, it would appear to be less likely that this would occur in larger plants, where the other losses scale up directly with the production rate.

C. Controls

Mercury emission control techniques for the hydrogen gas stream, end-box ventilation air stream, and cell room ventilation air stream fall into three general categories: cooling and demisting of air streams saturated or nearly saturated with vapor, chemical scrubbing, and adsorption. The following sections discuss each technique and its relative effectiveness.

1. Cooling and Demisting

If the partial pressure of mercury in the gas stream reaches the saturation point ("dewpoint") at a reasonably high temperature, mercury can be removed from the gas by cooling it below the saturation temperature to as low as desired or feasible and removing the condensed mercury droplets or supersaturated vapor with demisting equipment. Highly efficient demisting removes up to ninety-nine percent of the suspended droplets and super-saturated vapor, leading to high reductions in mercury vapor content because of the strong temperature dependence of the vapor pressure curve. For example, cooling the hydrogen gas stream from 210°F to 110°F reduces the vapor pressure of the mercury, and therefore the total mercury vapor per unit volume

of gas, by 97.5%, by weight. 100% demisting is required, of course, in order to remove all 97.5% of the mercury.

An extension of this technique involves compression of the gas before cooling and demisting. The demisting must be accomplished before the gas is allowed to expand to avoid revaporizing the coalesced mercury. As an example of this starting at 86°F, compression of the hydrogen stream to 3.5 atmospheres absolute followed by cooling to 68°F with demisting can reduce the mercury vapor by 55% by weight (Battelle Memorial Institute,1971). It should be noted that when the hydrogen gas is allowed to expand to one atmosphere pressure the mercury concentration would be below saturation. Cooling the gas to 37°F rather than 68°F would result in a 90% reduction in contained vapor.

Although full-scale application of these techniques to end-box ventilation air has not been reported as yet, it seems reasonable that they would be attempted in the near future.

2. Chemical Scrubbing

A depleted brine scrubbing system has been used since 1961 to treat the hydrogen stream of a domestic chlor-alkali facility. Exit mercury contractions of 0.1 mg/m^3 are reported for this facility.

The use of "chlorinated brine" to reduce mercury content of the gas stream below its saturated vapor pressure has been examined. The system used a solution of sodium hypochlorite, sodium chloride, and sodium hydroxide to produce soluble mercury salts which are then absorbed into the solution. Pilot plant operations indicated a reduction of mercury vapor to 1 mg/m^3 in the hydrogen gas stream, corresponding to a reduction of over 95% below cooling-demisting step results [Ref. 2]. Construction of a full-scale system was started. Subsequently, it was converted to a depleted brine system.

A hypochlorite scrubbing system is currently being used by the British Petroleum Company to treat both the end-box and hydrogen streams at one of their facilities. Chemical scrubbing appears to have promise for controlling mercury emissions at chlor-alkali plants.

3. Adsorption

The technique of chemical-physical adsorption of mercury is mechanically the simplest type of collection system. The contaminated gas stream is passed through a bed of the adsorbing medium and the mercury is preferentially trapped by either a chemical or physical adhesion process to the surface of the medium [Reference 2]. Depending upon the nature of the medium and the details of the adsorption process, the adsorbent may or may not be regenerable. In some cases it may also be possible to recover the mercury for reuse.

Adsorption of mercury on an appropriate medium occurs at virtually any concentration of the vapor down to almost trace levels. With adequate bed thickness and sufficiently low face velocity, and with the bed itself kept reasonably below saturation, it should be possible to reduce mercury concentrations in any gas to very low levels. Although some applications, notably for use on cell room air, still face full-scale trials, adsorption emission control techniques promise the ultimate in control of low-concentration mercury emissions.

Two types of media are currently being studied for their applicability to mercury emission control. The one upon which the most work has been done is activated carbon, either "plain" or "treated". The other medium is a molecular sieve, believed to be a zeolite-type material similar to those used in water deionization.

Activated charcoal, as noted above, may be used either with or without "treatment". The treatment appears to consist of impregnation of the charcoal with iodine and potassium iodide. Two manufacturers of charcoal are currently doing extensive research and development on this application of charcoal adsorption; one of them claims that its particular charcoal is regenerable. There is no indication as to the disposition made of the removed mercury. If non-reusable charcoal is used, there may be a significant disposal problem of spent charcoal, since the charcoal appears to become saturated with mercury after capture of about 10% mercury by weight. This could become a very high operating expenditure, since the charcoal becomes saturated

so readily. The charcoal adsorption technique would be used most effectively in "final" clean-up of gases which have a low concentration of mercury vapor.

Mercury emission control with a molecular sieve is a relatively new proprietary process for which many details are not available. However, it appears to operate in much the same manner as the charcoal adsorption system. Currently the manufacturer claims an installation in a 135 ton per day plant on the hydrogen gas stream. Two units are operated simultaneously with one acting as the collector while the other is being regenerated. Gas to be stripped of mercury vapor is first cooled and demisted to as low a concentration as practical. The gas is then passed through the collecting unit and either utilized or vented. Regeneration in the second unit reportedly involves bleeding off part of the cooled, demisted stream, heating it to about 650°F and passing it through the bed being regenerated to strip out the mercury. The mercury-laden regeneration gas is then returned to the cooling-demisting step for recovery of the mercury.

The exact emission reduction achieved by the molecular sieve process is not known; however, the manufacturer claims that the hydrogen gas leaving the process contains 0.50 mg/m^3 ppb .025 ppm) of mercury (private communications with EPA). Losses at this rate in the hydrogen from the plant where the process is currently being operated amount to approximately 4 lb/year. Presumably this is near the levels achievable by the activated charcoal adsorbents.

The primary advantages that the molecular sieve adsorbent has over activated charcoal are the demonstrated recoverability of the mercury, and the reusability and relatively long life of the medium (the molecular sieve manufacturer is reportedly willin to guarantee the bed for a minimum two-year lifetime). This may be offset by the difficulty of handling the heated hydrogen

regeneration stream and the added costs of heating and then cooling the regeneration hydrogen.

Technically, it would seem feasible to control both end-box ventilation air and cell room ventilation air with either one of the adsorption media. Even cell room ventilation air, with maximum permitted levels of 50 $\mu g/m^3$ of mercury, is reducible by at least a factor of five, based on the available data for pilot scale charcoal adsorption equipment operating on the hydrogen gas stream. However, it is not known at present whether trace gases found in end-box ventilation air and cell room ventilation air (predominantly ambient air) either positively or negatively affect the mercury absorption characteristics of either the charcoal or the "molecular sieve."

D. Preventive Controls

The extremely large volumes of cell room ventilation air that are currently used as the primary means of achieving the industrial hygiene TLV, plus the known sources of emissions into the cell room, suggest that "arrest-at-the-source" emission control procedures may be both more effective and more economical for cell room air. Sources of mercury emissions into the cell room air include the following:

1. Routine (process-required) emissions
   a. End-box sampling procedures.
   b. Removal of mercury butter from end boxes.
   c. Cell maintenance and rebuilding operations.
   d. Other mercury-connected maintenance work.
   e. Cell and mercury pump leaks.
2. Accidential (catastrophic) emissions)
   a. Accidental mercury spills.
   b. Cell failure.
   c. Other unusual circumstances.

It would appear that the emissions from category 1. are at least conceptually amenable to reduction by cell modification, improved maintenance procedures, and improved auxiliary equipment. It is not known whether any applicable technology has been utilized to the utmost with a view to reducing mercury emissions. To the extent that it is cheaper merely to provide adequate ventilation than it is to reduce emission losses, technological improvements are probably at a minimum. In addition, once adequate ventilating capacity is installed it is difficult to justify expensive improvements that would result in merely underutilizing the installed capacity.

Non-routine losses can be reduced by (1) reducing mercury handling requirements and (2) instituting improved shutdown procedures in instances of cell failure.

It is believed all of these steps are now being followed in varying degrees in maintaining the mercury level in the cell-room air below the new TLV of 50 $\mu g/m^3$. Some of the available means for implementing these practices are applicable to both new and existing facilities. A partial listing of the means which may be applied, for example, to the minimization of incidental spills includes:

- Devising and putting into practice improved routines for all normal cell-room operations that contribute to the incidental release of mercury.
- Providing special equipment required, for example, for the wet removal of cell butter.
- Improving maintenance procedures.
- Detecting and minimizing hot-hydrogen leaks.
- Devising procedures to deal with brine and caustic leaks from the cells and auxiliary systems.
- Taking steps to minimize leaks from the mercury pumps by improving pump maintenance procedures, or isolating the pumps from the cell-room atmosphere by enclosing them and collecting mercury that has leaked.

Some of the means for improving housekeeping procedures that have been suggested or applied include:

- Lining floors, sewerage, and channels with PVC or epoxy coatings.
- Removing mercury spills from floors and channels with vacuum sweepers.
- Rapid hosing down of floors and drains after leaks.
- Using mercury scavengers to inactivate spills that occur in hard-to-reach locations.

For new construction, the following steps have been recommended by Bouveng and Ullman in a paper presented in Stockholm, Sweden, in 1969:

- The use of improved cells designed to minimize leakage of the cell contents.
- Installation of numerous small mercury traps at strategic locations in the cell-room drain systems.
- The use of V-shaped rather than rectangular floor channels.
- The use of most of the means of controlling mercury emissions listed above.

It is suggested that individual operators need some latitude in choosing from among the control options suggested above to suit individual situation and needs [Reference 2].

E. Emission Standards

Standards for mercury emissions from mercury cell chlor-alkali plants used for this report are as follows:

- No more than .005 lb of mercury per ton of chlorine produced.
- No more than 2.56 lbs per day from any one plant.

A revised emission standard is currently under consideration by EPA. It limits mercury emissions to a maximum of 2300 grams (5 lbs) per day from any one plant (1300 gm/day for the cell room and 1000 gm/day for the combined process streams). Consideration of this standard is not included in this report. It would seem that significantly reduced control, and therefore costs and economic impact, than those shown below, would be required of the industry if the newer standard is adopted.

F. Costs of Control

The investment required to control emissions to the atmosphere by mercury-cell plants of average size (approximately 240 tons per day) is estimated to be $14,725,000 (Table 4-7). Annualized costs are estimated to be $17,344,200. This amounts to an investment of $1,950 and an annualized cost of $2,300 per ton per day of chlorine plant capacity.

Control cost will increase plant investment from five to ten percent and will increase production costs about five percent for mercury-cell plants. Cost changes of this magnitude will have a significant impact on the economics of mercury cell production versus diaphragm cell production. The two processes appear to be very similar in production costs. However, mercury cell production was apparently favored in recent years since the majority of new construction (through 1970) has been mercury cell plants. Addition of control cost to mercury cell plants will cause diaphragm cell plants to be more economical since the latter require no controls. This will cause new construction to be shifted to diaphragm cell plants. Modern mercury cell plants are efficient enough so that they can be adequately controlled and remain competitive in the industry. Only those mercury cell plants that are already obsolete and marginal will be abandoned as a result of the imposition of air pollution emission control costs.

Costs of control to consumers will decrease by 1977 to an investment of $12,650,000 and an annualized cost of $14,900,000, even though total industry production will increase to 13,375,000 tons of chlorine.

Table 4-7. ESTIMATED COSTS FOR CONTROLLING EMISSIONS FROM THE MERCURY CELL CHLOR-ALKALI INDUSTRY, 1970 AND 1977

Year	Estimated Chlorine Production		Required Investment	Annualized Cost
	Industry	Mercury Cell		
1970	8,895,200 tons	3,180,400 tons	$14,725,000	$17,344,000
1977	13,375,000 tons	2,663,800 tons	$12,650,000	$14,900,000

These estimates are based on the assumption that industry production will increase at the rate of six percent per year but that mercury cell production will decrease at the rate of 2.5 percent per year through 1977. The assumption of decreased mercury cell production is based on a shift in economics that favors diaphragm cells, causing industry to construct diaphragm cell plants to replace mercury cell plants as they become obsolete.

G. Economic Impact

1. Industry Structure

For the chlor-alkali industry as a whole, there were 35 firms manufacturing and selling chlorine and caustic in the open market. These firms operated 85 plants. Thirty-one of these are mercury cell plants owned by 16 different firms. Seven firms operated only a single mercury cell plant. With the exception of one firm, the single plant firms are among the major industrial firms in the country. Most chlor-alkali manufacturers are large multiproduct chemical companies or are vertically integrated industries that use chlorine, caustic, or both, in their manufacturing process. Most of the chlorine plants in the country have a captive market for at least a part of their production.

The chlor-alkali industry is moderately concentrated and displays remarkably stable price schedules. However, effective long run collusion does not appear likely even though the nine largest chlorine-caustic producers were charged with conspiracy and price fixing. Almost every producer uses some or most of his production in his own operation and sells the excess. The barriers to entry into production are not great. The minimum efficient plant is not large compared to total production and the technology is readily available. Finally, the products are highly standardized and little production differentiation is possible. In the long run, effective competition can be expected because new sellers can enter the

market or consumers can integrate backwards into chlor-alkali production (and perhaps sell their excess production) restoring competition, if monopoly profits develop.

2. Production and Consumption

The weighted average capacity of mercury cell chlorine plants in the United States is 244 tons per day. In 1970 approximately 8.9 million tons of chlorine valued at $667.1 million and 10.1 million tons of caustic valued at $664.9 million were produced by all processes in the U. S. (Table 4-8). Mercury cell production was 3.2 million tons of chlorine and 3.5 million tons of caustic valued at $238.5 million and $230.9 million, respectively.

In 1970, production of chlorine was down 5.5 percent from the 1969 record high production of 9.4 million tons (Table 4-9). This, however, is still above 1968 production. Growth in production has been interrupted only three times since World War II and has increased at a compound rate of 6.7 percent since 1960.

Chlorine and caustic consumption are expected to continue growing for the next several years. The estimated rate of growth for the next five years approximates six percent. No major technological changes are anticipated in the next 10 years that will adversely affect the total demand for these products. One new technological development promises increased electrical efficiencies to both mercury and diaphragm cells. It is a rhodium-plated titanium anode.

3. Prices and Trends

Current prices are 3.75 cents per pound or $75.00 per ton for chlorine (Table 4-10) and 3.30 cents per pound or $66.00 per ton for caustic (Table 4-11). Chlorine prices are up from last year; caustic remains the same. This continues a rather remarkable record. There has not been a decrease in published prices for either product since 1939, although discounting arrangements may have at times reduced actual prices. Prices

Table 4-8. 1970 VOLUME AND VALUE OF CHLORINE AND SODIUM HYDROXIDE PRODUCED BY MERCURY CELL AND ALL PROCESSES IN THE U.S.

	All Processes		Mercury Cell Process	
	Chlorine	Sodium Hydroxide	Chlorine	Sodium Hydroxide
Tons of Product	8,895,200	10,073,700	3,180,400	3,498,200
Value	$667,140,000	$664,864,200	$238,530,000	$230,881,200

Table 4-9. U.S. PRODUCTION OF CHLORINE: 1941-1970

Year	Thousands of Short Tons
1941	800.8
1942	989.8
1943	1,214.4
1944	1,262.4
1945	1,192.1
1946	1,165.1
1947	1,443.2
1948	1,640.0
1949	1,767.0
1950	2,084.2
1951	2,517.9
1952	2,608.7
1953	2,797.3
1954	2,903.7
1955	3,421.1
1956	3,797.7
1957	3,947.7
1958	3,604.5
1959	4,347.1
1960	4,636.9
1961	4,600.8
1962	5,142.9
1963	5,464.1
1964	5,945.2
1965	6,517
1966	7,204
1967	7,680
1968	8,428
1969	9,422
1970	8,895

Source: Bureau of the Census, Current Industrial Reports; Stanford Research Institute, Chemical Economics Handbook, 732.40308

Table 4-10. CHLORINE - PRICE HISTORY

	Liquid	
	Cents Per Pound	Dollars Per Ton
1930	2.40	48.0
1931	1.75	35.0
1932	1.75	35.0
1933	1.75	35.0
1934	1.85	37.0
1935	2.00	40.0
1936	2.15	43.0
1937	2.15	43.0
1938	2.15	43.0
1939	1.75	35.0
1940	1.75	35.0
1941	1.75	35.0
1942	1.75	35.0
1943	1.75	35.0
1944	1.75	35.0
1945	1.75	35.0
1946	1.75	35.0
1947	2.00	40.0
1948	2.25	45.0
1949	2.40	48.0
1950	2.55	51.0
1951	2.70	54.0
1952	2.70	54.0
1953	2.70	54.0
1954	2.93	58.6
1955	2.93	58.6
1956	3.05	61.0
1957	3.15	63.0
1958	3.15	63.0
1959	3.15	63.0
1960	3.25	65.0
1961	3.25	65.0
1962	3.25	65.0
1963	3.25	65.0
1964	3.25	65.0
1965	3.25	65.0
1966	3.25	65.0
1967	3.35	67.0
1968	3.45	69.0
1969	3.65	73.0
1970	3.75	75.0

Price Bases Are:

1930-1932	Tanks, Works
1933	Tanks, Works, Freight Equalized
1934-1970	Tanks, Single Units, Works, Freight Equalized

Prices are given in the source as dollars per 100 pounds, and the price is calculated from this.

Source: Oil, Paint and Drug Reporter

Table 4-11. SODIUM HYDROXIDE - PRICE HISTORY
(CENTS PER POUND)

	Liquid	Solid (76% Na_2O)
1930	--	2.95
1931	--	2.55
1932	--	2.55
1933	--	2.90
1934	--	2.60
1935	2.25	2.60
1936	2.25	2.60
1937	2.25	2.60
1938	1.98	2.30
1939	1.95	2.30
1940	1.95	2.30
1941	1.95	2.30
1942	1.95	2.30
1943	1.95	2.30
1944	1.95	2.30
1945	1.95	2.30
1946	1.95	2.30
1947	2.10	2.50
1948	2.40	3.05
1949	2.40	3.05
1950	2.40	3.20
1951	2.55	3.35
1952	2.55	3.35
1953	2.55	3.70
1954	2.55	3.70
1955	2.70	3.85
1956	2.80	4.10
1957	2.90	4.30
1958	2.90	4.80
1959	2.90	4.80
1960	2.90	4.80
1961	2.90	4.80
1962	2.90	4.80
1963	2.90	4.80
1964	2.90	4.80
1965	2.90	4.80
1966	2.90	4.80
1967	3.00	5.15
1968	3.00	5.15
1969	3.30	5.35
1970	3.30	5.80

Liquid: Price Bases Are:

1934-1946	49-49% NaOH, Sellers' Tanks, Works
1947-1970	50% NaOH, Sellers' Tanks, Works, Dry Basis

Solid (76% Na_2O): Price Bases Are:

1930-1933	Drums, Carlots
1934-1966	Drums, Carlots, Works
1967-1970	700-pound Drums, Carlots, Works

Source: Oil, Paint and Drug Reporter

have increased at a compound rate of 1.4 percent for chlorine and 1.3 percent for caustic since 1960.

The lower purity caustic from diaphragm cells is normally sold at a discount with the amount of discount depending on the quantity sold, destination, and the region of the country. Along the Gulf Coast the market is softer than in the Northeast and the discount may reach 10 percent. In the Northeast, the discount is generally five to seven percent (Charles River Associates, 1969).

4. Price Impact

Prices for chlorine and caustic can be expected to go up. The industry as a whole is competitive and profit margins are so narrow that the cost increase cannot be entirely absorbed. The portion of the market served by mercury cell plants, about 35 percent, is so large that diaphragm cell plants cannot serve the entire market without shortages that would put upward pressure on prices. This would allow at least some mercury cell plants to survive but not without an overall increase in prices.

The size of the price increase is a question not easily answered. An increase of $0.92 per ton across the entire 1970 production of chlorine and caustic would cover the increased production costs and would be the upper limit to price increases. However, about 65 percent of the industry is not affected by the cost increase. If a price increase in the range of $0.90-$0.95 was attempted, price cutting by diaphragm cell plants to capture a bigger share of the market could be expected so that an increase of this size could not be maintained. Where and when prices would eventually stabilize is unknown. An increase of $0.55 to $0.65 might be a reasonable estimate.

5. Impact on Competition

Control costs of the amount reported in Table 4-7 should have little adverse affect on the companies producing chlor-alkali. Most have captive markets where chlorine or caustic are minor costs in the product produced for at least part of their production. Three-fourths of the companies have both mercury cell and diaphragm cell plants. While eight firms use only the mercury cell process, only one depends on chlor-alkali production for the bulk of its sales. Only one multiplant firm has only mercury cell plants.

The biggest impact on competition will be on that between mercury cells and diaphragm cells. It appears that the diaphragm cell will now be more economical but the mercury cell will not be so adversely affected that it will be entirely abandoned.

6. Investment Impact

Firms in the chlor-alkali industry should have no difficulty obtaining the necessary capital to install air pollution control equipment. Sales from the average size chlor-alkali plant are in excess of $12 million. The construction costs of such a plant are high enough that only financially strong companies are in the industry. For most firms in the industry, chlor-alkali sales make up only a minor part of total sales.

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